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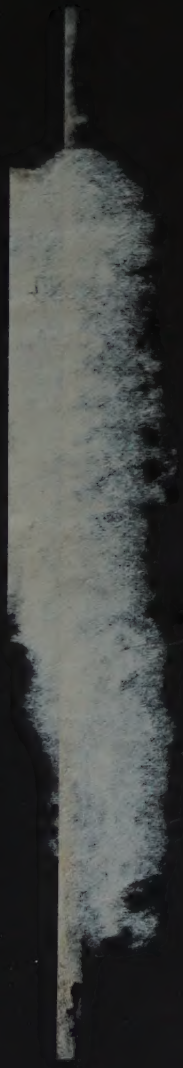

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FORMERLY CONSULTING METALLURGIST AND ANALYTICAL CHEMIST TO THE INDIAN GOVERNMENT, ROYAL INDIAN ENGINEERING COLLEGE, COOPERS HILL;

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PREFACE.

SINCE the publication of the first edition of this work considerable advances have been made in the various departments of Steel Manufacture, necessitating the addition of new matter to each edition, while the amount of letterpress which it has been found possible to delete has been comparatively small; the volume has thus been gradually increased in size, until it has become too cumbersome for convenient handling. It has therefore been decided to divide the present edition into two volumes, the first dealing with the Manufacture and Metallurgy of Steel and the Physical Properties of Finished Steel, and the second volume covering the matter dealt with in former editions by Mr. J. W. Hall in the section on "The Mechanical Treatment of Steel."

The scheme of the work has not been altered, but only such additions and modifications have been made as have been rendered necessary by the advancement in the theory and the practice of the art.

In the first volume drawings showing the latest modifications in open hearth furnaces and the latest types of charging machines and gas producers have been introduced, and in the chapter on the Basic Open Hearth recent developments and modifications are described and discussed; the chapter on Electric Smelting has also been brought, as far as possible, up to date. Various additions have been made to what may be called the more theoretical chapters, embodying the results of the latest research in the different branches, and a complete set of new photo-micrographs has been prepared to replace those in the last edition. Several Plans of various new installations, illustrating the general designs of the most modern works erected in Europe and America, have also been added.

In the second volume on the Mechanical Treatment of Steel, for which Mr. Hall is entirely responsible, the various chapters have been brought up to date and additions made to illustrate developments in modern steel-works' practice. The provision of power for use in steel works is treated much more fully. To the chapter on Steam Engines has been added a section on the use of steam in exhaust steam turbines. Entirely new chapters have been added dealing with the Generation of Steam by Solid Fuel and Waste Gases, on the Production of Power by Gas Engines working with Blast-Furnace Gases, and on Electric Driving of the Mills. Comparisons are made between these various systems of working.

We have to thank Mr. E. F. Law, Associate of the Royal School of Mines, for his assistance in preparation of the new photo-micrographs, and we are also greatly indebted to Mr. C. O. Bannister, A.R.S.M., Head of the Metallurgical Department of the Sir John Cass Institute, for reading the proofs of the first volume, for the preparation of Index, and for seeing the first volume to press.

F. W. HARBORD.
J. W. HALL.

October, 1911.

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THE METALLURGY OF STEEL.

SECTION I.

INTRODUCTION.

During the last fifty-five years the introduction of the Bessemer or Open Hearth process has not only revolutionised the steel manufacture of the world, but has compelled us to revise our definition of steel. Before 1856, the year in which Bessemer first published the particulars of his great discovery, there were practically only two varieties of steel in the market—viz., crucible or cast steel, and shear steel—although small quantities of puddled steel and steel made direct from the ore were produced.

Crucible or cast steel was made by melting blister steel bars containing different percentages of Carbon, according to the grade required, with small percentages of steel scrap in crucibles, and casting the fluid metal into small iron moulds, the ingots thus obtained being afterwards forged down to the required size and shape. The percentage of Carbon in such steels usually varied from ·25 to 1·75, although sometimes it was higher. Shear steel was made by piling and welding together plated, cemented, or blister bars into what was known as a "faggot," and afterwards forging and rolling this faggot down into thin strips, suitable for the manufacture of cutlery.

The distinguishing features of these classes of steels were, that by rapid cooling from a red heat by quenching in water, they became extremely hard and more or less brittle, and that by re-heating to different temperatures, or "tempering," this hardness could be modified, the brittleness removed, and great elasticity, combined with varying degrees of hardness conferred upon the steel. The maximum degree of hardness which each steel was capable of taking depended upon the Carbon content, the higher the percentage of Carbon, the greater the hardening power of the steel; and the use of crucible and shear steel was practically confined to the manufacture of cutlery, tools, &c., and some special parts of machines which required a material which could be hardened after it had been forged or machined into shape. For structural purposes wrought iron and cast iron were the materials almost, if not quite, exclusively employed, the former possessing properties which enabled it to be wrought or forged into any required shape, and the latter being moulded into different forms by pouring it, while in a molten condition, into moulds of the required shape. The chief distinction between wrought iron and steel was that the former was not hardened by rapid cooling in water from a red heat, and contained always less than 0·20 per cent. of Carbon, and generally less than 0·10. Cast iron, on the other hand, contained from 2·5 to 4·0 per cent. of Carbon, and was distinguished from both steel and wrought iron by being

brittle at a red heat, and incapable of being wrought or forged, and by having a comparatively low melting point of from 1,075° to 1,276° C., against 1,600° C., or higher, for wrought iron. Thus steel at this period, as regards percentage of Carbon, was an intermediate product between wrought iron on the one hand and cast iron on the other.

The advent of the Bessemer process furnished a material which, as regards the process of manufacture, resembled crucible steel, being cast from a fluid condition into moulds, and afterwards forged into shape, while it possessed practically none of the properties of cast crucible steel, and both physically and chemically was almost identical with wrought iron. Thus it frequently contained 0·10 per cent., or less, of Carbon, and on quenching from a red heat in water did not appreciably harden. Such material, made by the Bessemer or Open Hearth processes, and containing less than 0·20 per cent. of Carbon, has become generally known as "mild steel."

Steel containing much larger percentages of Carbon, and, indeed, anything up to 2·0 per cent., can be made either by the Bessemer or Open Hearth process, and such steels, as regards hardening and tempering, possess similar properties to crucible cast steel; in fact, this capacity for hardening depends upon the percentage of Carbon present, irrespective of the process of manufacture.

It is very difficult to define the term steel as now generally employed, and almost impossible to frame a definition that shall include crucible cast steel, shear steel, and the numerous grades of Bessemer and Siemens steel, as to define them involves a description of each process of manufacture. It is possible, however, to give a general definition which will include all grades of Bessemer and Siemens steels, and distinguish these from wrought or puddled iron on the one hand and from cast iron on the other.

Definition of Steel.—Steel, using the term as applied to the metal produced by the Bessemer and Open Hearth processes, may be defined as purified pig-iron, which, unlike wrought iron, has been cast whilst in a molten state, and in which the Carbon and impurities present in the original pig-iron have been reduced (1) by oxidation alone, (2) by dilution with a previously purified metal, or (3) by oxidation and dilution combined, *to such a point that the ingot cast is capable of being forged or rolled into blooms, slabs,* &c. This definition does not define the extent to which the various impurities, such as Silicon, Sulphur, Phosphorus, Manganese, &c., present in the pig-iron must be removed before the finished metal can reasonably be regarded as steel. Unlike Carbon, they are not essential constituents of a given grade of steel, but simply impurities which usually have an injurious influence, and determine whether the steel is of good or bad quality, and suitable or otherwise for a particular purpose, without affecting the broad question as to the material being steel or not. The best conditions for the decarburisation and the removal of the various impurities of pig-iron largely constitute what is understood by the Metallurgy of Steel, which may be defined as the art of decarburising and purifying pig-iron, and of producing cast ingots containing various percentages of Carbon as free as possible from impurities, and the subsequent manufacture therefrom of finished bars, plates, and other shapes of different degrees of hardness, strength, and ductility to suit the requirements of modern engineering practice. Such bars, plates, &c., must be free from "red shortness"—*i.e.*, they must be capable of being forged at all temperatures from a red to a welding heat without showing any signs of cracking or other defects. They must further be free from "cold shortness"—*i.e.*, must not show any signs of brittleness under sudden shock or under

a steadily applied load in the cold condition, the stress which each steel may reasonably be expected to bear varying with its content of Carbon. Although it is impossible to draw an absolutely hard and fast line based on chemical analysis between steel and various forms of cast iron, so far as Bessemer, Open Hearth, Crucible Cast Steel, and Shear Steel are concerned, metal containing over 2·3 per cent. of Carbon may reasonably be classified as cast iron. The above limitation does not apply to some special varieties of steel, such as Indian Wootz, in which occasionally the Carbon is as high as 2·70 per cent., but these, although true steels, are not of sufficient commercial importance to materially affect the above definition.

CHAPTER I.

THE BESSEMER PROCESS.

So much has been written about the general history of the Bessemer process that it is not intended to devote much space to this aspect of the subject, while, happily, as regards the metallurgy of the process there is very little to relate. The process stands almost alone amongst our large manufacturing industries, in that it is carried on to day substantially in the same manner as it was nearly fifty years ago, at the works erected at Sheffield by the late Sir Henry Bessemer and his partners; the only improvements that have been introduced being in detailed mechanical arrangements and larger appliances. Since Bessemer read his paper at the Cheltenham Meeting of the British Association on August 11th, 1856, on "The Manufacture of Malleable Iron and Steel without Fuel," and recognised the necessity of Manganese as an addition, as suggested by R. Mushet in his patent of September 22nd, 1856, the process has not been appreciably modified. The Basic Bessemer process, which will be described later on, is simply the application of the Bessemer principle to the treatment of Phosphoric Pig-Iron, and the carrying out of the Bessemer process under special conditions, the fundamental principle of the oxidation of the impurities in cast iron by the blowing of air through it in a molten state remaining unaltered.

By the combustion or oxidation of the impurities—*i.e.*, the Carbon, Silicon, Manganese, &c., in the cast iron used—sufficient heat is developed to maintain the purified metal in a fluid condition, so that it can be cast into suitable moulds, and afterwards forged or rolled to any required form.

The Converter.—The molten cast iron from the blast furnace or cupola is transferred to a vessel, known as the "converter," lined with highly refractory silicious material in which there is, fixed in the bottom itself or through the sides near the bottom, a number of fire-bricks with small holes in them, known as twyers, through which the air under pressure from a blowing engine passes into the metal. The original Bessemer converter was a fixed vessel with air inlets at the sides, but this was at a very early date almost entirely replaced by a tipping converter, supported on trunnions, in which the air was injected at the bottom. Fig. 1 is a drawing of the original fixed converter used by Bessemer at his experimental works at St. Pancras in 1856. It was soon found that the air did not penetrate into the centre of the

molten bath, but escaped through the metal at a very short distance from the orifice of the twyer, and rapidly cut away the brick lining. To overcome this difficulty a converter with a twyer at the bottom, with a varying number of air holes, was designed, and is shown in fig. 2. Fig. 3

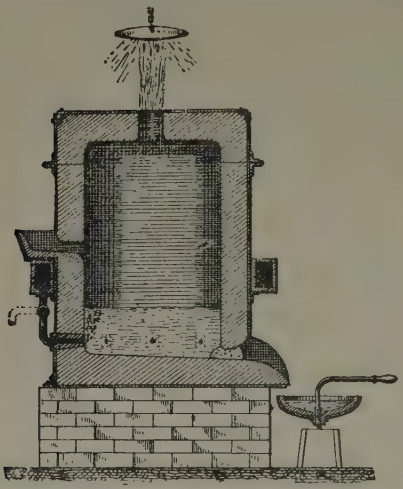


Fig. 1.—Original Bessemer Converter, lined with 4½-inch Stourbridge bricks. A cast-iron tubular ring, shown in cross-section, surrounds the converter, and from it six branch pipes descend to the twyers near the bottom of the converter. The branch pipes had elbow joints so that they could be moved into position, shown by dotted lines, to enable the twyers to be cleaned or repaired.

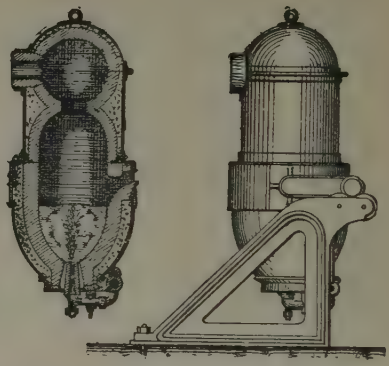


Fig. 2.—First converter with twyer at bottom. Covered at the top to prevent ejection of metal.

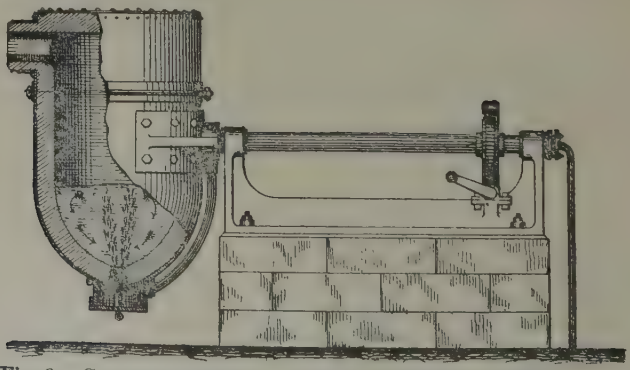


Fig. 3.—Converter designed so that blow could be stopped at any moment by rotating the converter into the horizontal position, and thus removing the centre twyer above the level of the bath of metal.

shows a further development of the same idea, the converter being tipped by worm-wheel gearing, and made of such diameter that when the converter was rotated into the horizontal position, the twyer would rise

above the surface of the metal, and enable the blow to be stopped at any particular moment. In Sweden, in these early days of the process, side-blowing fixed converters gave good results, but as the twyers were always beneath the metal, it was impossible to stop the blow without removing the fluid iron. To meet this difficulty, and still retain the side-blowing, the converter shown in figs. 4 and 5 was designed. This, when tilted

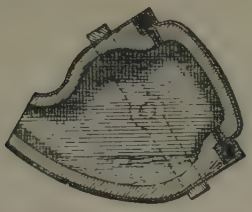


Fig. 4.—Converter at end of blow with twyer above the bath.

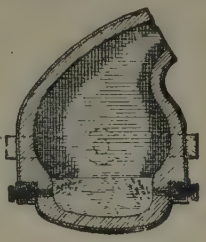


Fig. 5.—Side-blowing tipping converter in position for blowing.

into the position shown in fig. 4, raises the twyers above the bath of metal. Fig. 6 is a sketch of what may be regarded as the first Bessemer converter of the form now commonly employed. This converter was erected at the works of Sir Henry Bessemer, at Sheffield, and the drawing is a copy from the original plans.

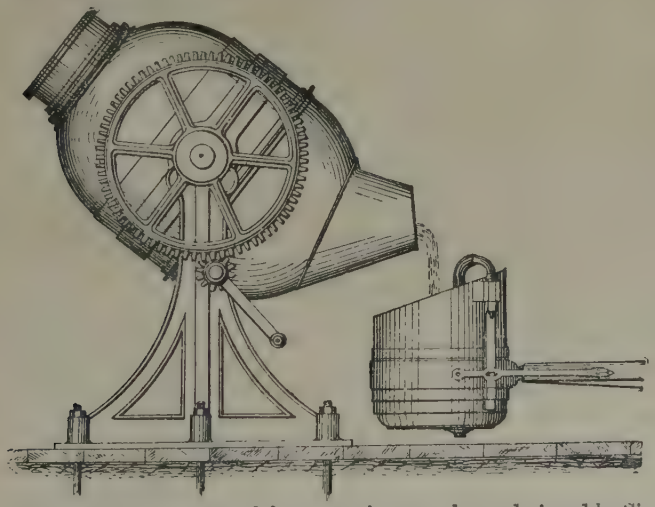


Fig. 6.—First converter of form now in general use designed by Sir Henry Bessemer for his works in Sheffield. Showing metal being poured into ladle after completion of the blow.

General Description of Process.—In carrying out the process, the molten iron is poured into a converter similar to that shown in fig. 7, and air is blown through the bottom twyer holes until practically the whole of the Carbon, Silicon, and Manganese has been oxidised, when an alloy of Iron and Manganese, known either as Spiegeleisen or Ferro-manganese, is added, and the liquid metal (which is now steel) is poured into a large

cauldron or ladle, from which it is teemed into cast-iron moulds, usually rectangular in section with rounded corners, but of varying sizes, and known as ingot moulds. After a short time the liquid metal sets or "freezes," and is then drawn from these moulds, reheated, and rolled or hammered into any required shape.

The Modern Converter.—The modern converter is a pear-shaped vessel, built of mild steel, or of wrought-iron plates rivetted together, and is lined with siliceous material. This lining may be built up with silica bricks, or with a clay-like material, known as ganister, which may be rammed round the inside of the casing. The converter is supported on trunnions, one of which is hollow, and connected with the blast main through which the air from the blowing engine passes to the blast-box under the bottom of the converter (see figs. 7, 8, 9 and 10, Plate i.). The body of the converter is mounted in a trunnion ring, to which it is firmly bolted, as are also the trunnions. This ring may be a steel casting in one piece or in sections, or it may be built up of $1\frac{1}{2}$ to 2-inch mild steel or wrought-iron plates. In the case of small converters, a strong, heavy, cast-iron ring may be used. In all the early Bessemer converters the entire shell was rivetted together, but in the modern vessel the bottom portion is always, and the nose or upper part generally made detachable, being usually cottered, or bolted, to the centre portion of the vessel. The converter is thus divided into three portions known as the bottom section, the belly, and the nose. Owing to the very rapid wear which takes place round the twyers, probably no improvement in Bessemer practice has done more to facilitate rapid work than the invention of the detachable bottom by the late Mr. Alex. L. Holley, the well-known American Engineer. The full advantage of this device will be appreciated when it is mentioned that the lining in the bottom containing the plug or twyer portion is generally worn away in about 12 to 15 blows, and sometimes fewer, while the lining of the belly of the converter usually lasts for three or four, and sometimes for twelve months, or even longer. The nose of the vessel is not often removed, except when the converter is entirely relined, and not always even then, but it is a distinct advantage to be able to uncotter it if necessary. In the centre of the bottom section is what is known as the plug, in which are fixed a number of fireclay twyers, K, K, K (fig. 10), each containing about 12 or 18 holes from $\frac{1}{4}$ inch to $\frac{3}{8}$ inch in diameter through which the air is forced into the molten metal from the blast main. The entire bottom section, with the exception of these twyers, is made of siliceous material, such as rammed ganister, and after drying is fixed on the vessel by means of lugs or links and cotter pins, as shown in fig. 7. G is the blast-box, underneath the bottom section, which receives the air direct from the blast pipe before it enters the twyers. It is very important that the bottom plate of this blast-box should be easily removable, so that the twyers can be readily examined and repaired or renewed if necessary during a blow, and at the same time it must be perfectly air-tight to prevent waste of blast. This is usually effected by having it faced true, giving a good wide bearing, putting yarn and clay packing round the bottom plate between it and the box, and securing the plate by a large number of cotters to the blast-box.

There are two forms of converters known as eccentric and concentric, according to the shape of the nose or upper section. They are shown in part section and part end elevation in figs. 8 and 9, and it will be seen that the eccentric has the upper part of the converter straight on one side, and curved on the other, while in the concentric one, this part forms a frustum of a cone, the sides being inclined equally to the axis of the converter.

PLATE I.—Modern 16-Ton *Bessemer* Converter.

[*To face page 6.*

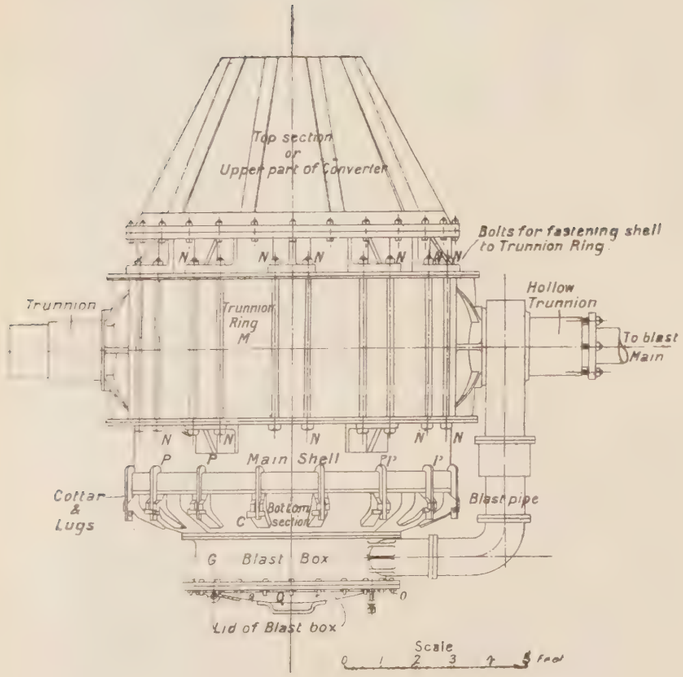


Fig. 7.—Elevation of Converter, showing blast main, blast box, details of shell; and method of fixing bottom section to the body of converter with lugs and cottars. N, Brackets and bolts for fastening shell to trunnion ring; P, lugs and cottars for fastening bottom section to body of converter; G, blast box; O, cottars for fastening lid on to blast box.

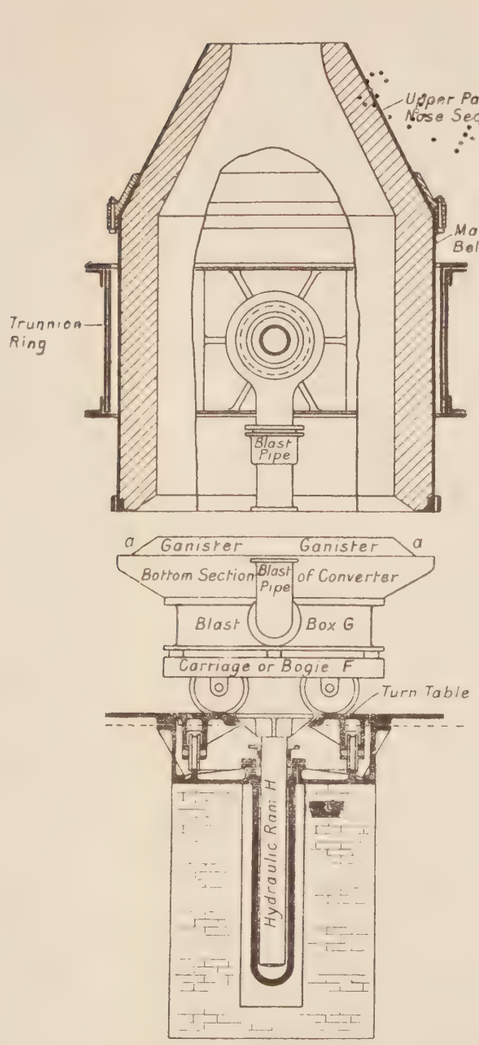


Fig. 8.—Concentric Converter in part section and end elevation, with bottom section on bogie ready to be lifted by hydraulic ram.

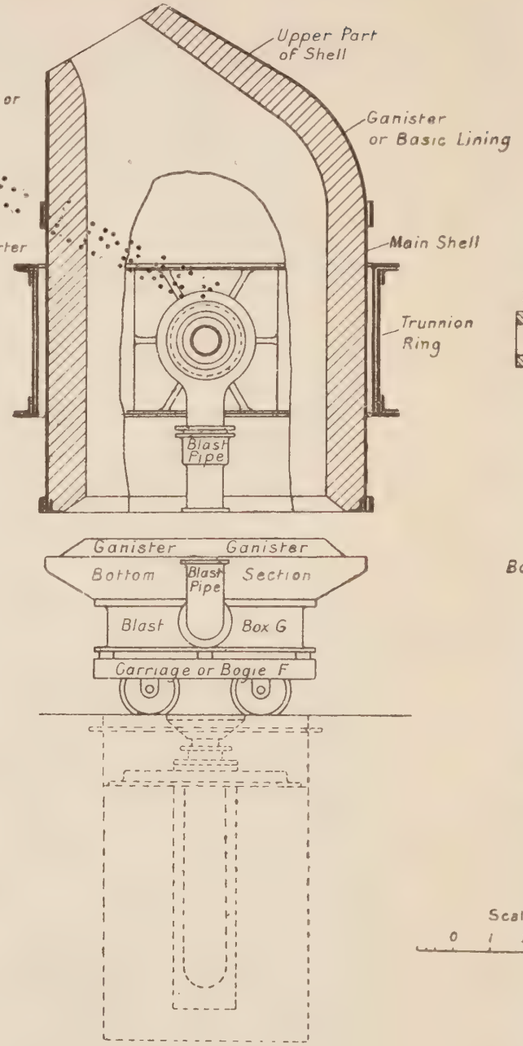


Fig. 9.—Eccentric Converter in part section and end elevation.

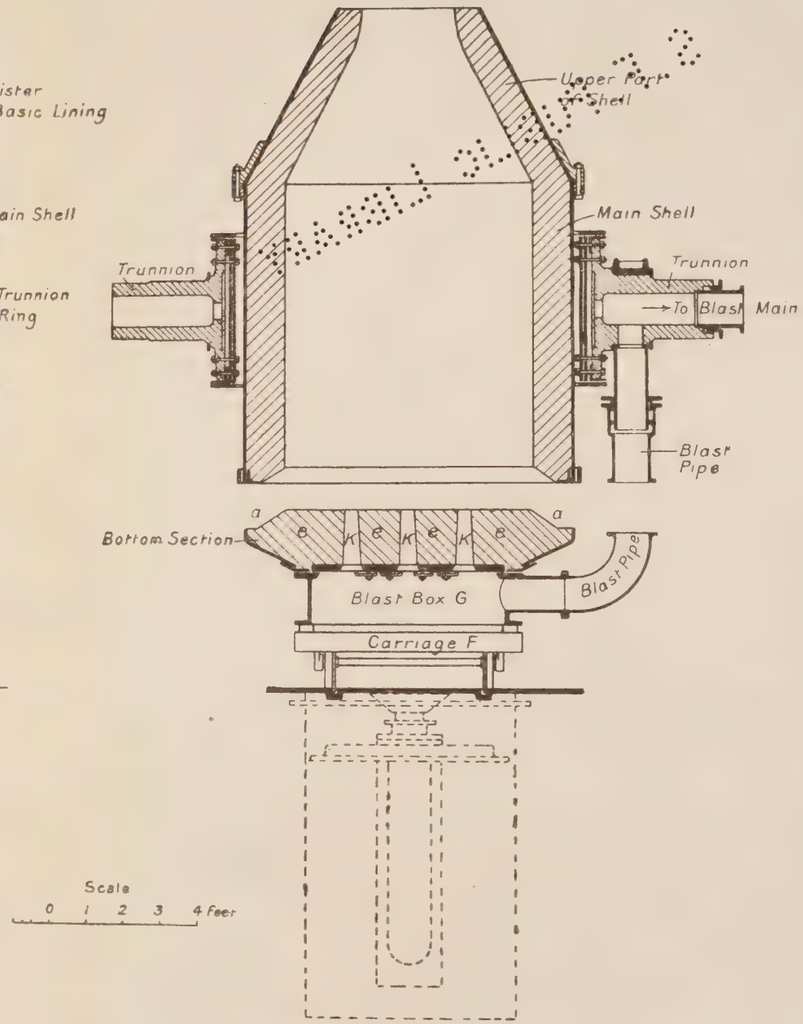


Fig. 10.—Vertical Section of Converter through the Trunnions, showing blast main. The bottom section shows the twyers in position. K K K, twyers; *eee*, rammed ganister.

In fig. 10 a converter is shown in vertical section through the trunnion and blast main, the bottom section being detached but ready in position for fixing on to the body of the vessel. When fixing the bottom section to the converter, it is raised by the hydraulic ram shown underneath, and firmly secured by means of cotter pins and lugs.

Rotating the Converter.—A very strong iron framework supported on columns carries the converter on suitable bearings, so arranged that the vessel can be rotated on its trunnions through an angle of at least 180°. The rotation is usually effected by means of a pinion keyed on to one of the trunnions, gearing into a rack attached to the end of a double-acting hydraulic ram. The position of the hydraulic ram and cylinder may be either vertical above or below the level of the converter trunnion, or may be horizontal as shown in the sketch (fig. 11). Both the rack and

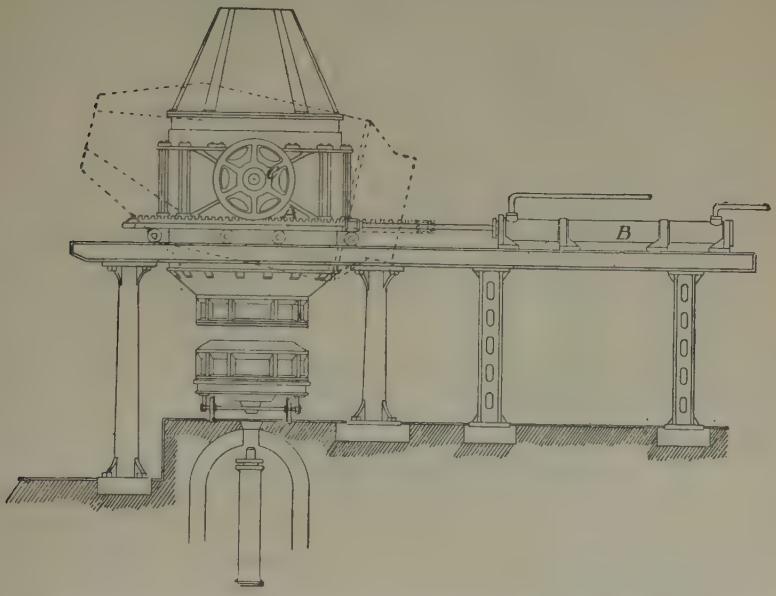


Fig. 11.—Method of Rotating Converter by Hydraulic Rack.—A, Rack ; B, hydraulic cylinder ; C, pinion.

pinion and the ram must be securely cased in sheet-iron to prevent injury by metal or slag splashing upon them. The valves of the hydraulic cylinder are usually controlled at some considerable distance from the converter, from a raised platform known as the pulpit. When the converter is ready to receive a charge of molten metal it is rotated into the horizontal position shown by the dotted lines in fig. 11, and the metal is poured in from a ladle through the nose of the vessel. When in this position the bottom portion of the vessel or converter containing the twyers is above the level of the metal bath, and before rotating to the vertical position for blowing, the air blast, which is of sufficient pressure to overcome the head of metal, is turned on, and prevents the latter from entering the twyer holes or air passages.

In some cases the rotation is effected by a worm and pinion gear, actuated by a hydraulic engine, or by a double or triple cylinder steam engine. In addition to some other advantages, this allows of a complete

revolution of the vessel through 360°, while with a rack the movement is much more restricted. The simplicity and strength, however, of the rack and pinion arrangement, and the facility with which it can be manipulated, have made its adoption general, and there can be but little doubt that it is the more suitable for steel works practice.

Lining of the Vessel.—The vessel may either be lined with silica fire brick, built in with very thin Silica cement, making the joints as small as possible, or it may be rammed up entirely with moist ganister, a very infusible siliceous material with just sufficient clay combined with it to enable it to bind when well rammed in a moist condition. If bricked,

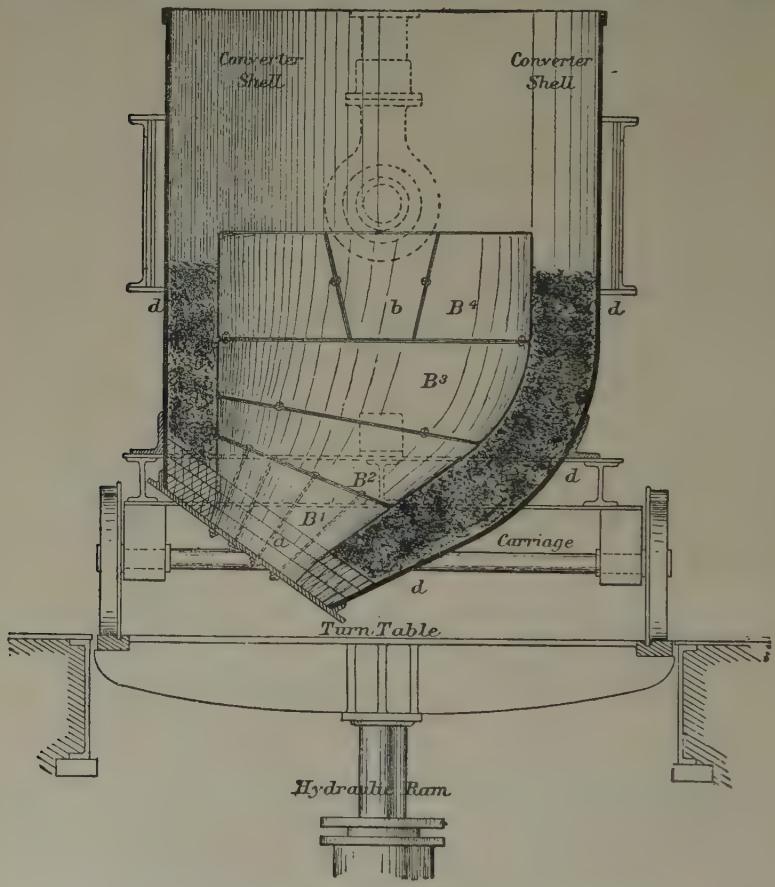


Fig. 12.—Ramming Converter. Core shown in position.

special bricks made to the sweep of the vessel are necessary to obtain a satisfactory result, as otherwise, more or less wide joints will be left in the brickwork, and the molten metal will soon find its way into these, and lead to the rapid destruction of the lining. Bricks, however, are now rarely used, a rammed ganister lining being almost universally employed. When a new shell is to be lined by ramming, the vessel is usually turned upside down, the bottom section having been previously taken off, and the mouth covered with boards or iron plates to afford a base, and two or three

courses of best silica bricks are built round the bottom of the nose section. Wooden or metal cores, made in sections to the sweep of different parts of the vessel, are then placed inside, and the annular space between these cores and the shell of the vessel is rammed with moist ganister by the aid of heavy iron rammers. The cores are generally made in taper segments, for easy withdrawal after the ramming is finished.

In some cases the lining of the vessel is done while it is supported in its bearings as usual, only in the inverted position, but when a plant is working up to the full extent of its output a spare converter is generally kept ready lined, the worn out one being removed and taken away to the repairing shop and replaced by the relined converter. The removal of the converter from its bearings may be effected by an overhead crane, or by a carriage on a hydraulic lift and a turntable underneath the converter as shown in the sketch (fig. 8, Plate i.) By means of the latter the converter is lifted up clear of the bearings, and the whole turned round through an angle of 90°, so that the trunnions will clear the girders supporting the bearings, and then lowered to the level of the rail track, and drawn away to the repairing shop.

Fig. 12 shows the method of lining a converter by ramming, and fig. 13 shows the core with taper sections in the cylindrical portions to facilitate removal after the ramming is completed. After a few rings of bricks have been built into the end of the nose section, for 18 inches to 2 feet, the first part of the core is fixed on these, and bolted to the plate *a* (fig. 12), and men, standing on a platform inside, ram up the ganister level with the core. Then another section of the core is bolted on and the ramming continued, and so on until the lining is completed to the required height.

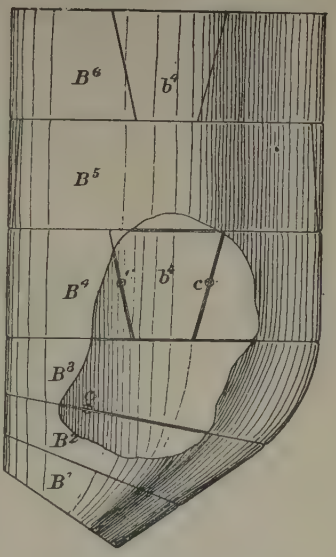


Fig. 13.—Metal or Wooden Core for Ramming Converter.

Instead of using cores sometimes a dry brick wall is built up inside the vessel, and the annular space between this and the shell rammed with ganister. When the lining of the vessel is completed, it is returned to its position in the Bessemer shop, a guard ring being fixed round the bottom to prevent the lining falling away. Having been rotated to its upright position, the bottom section is cottered on in the usual way, and a fire lit in the bottom of the converter, and urged by a gentle blast through the twyers until the whole lining is completely dried.

Details of Bottom Section.—The bottom section consists of the centre containing the fire-brick twyers, supported by a cast-iron plate known as the "bottom plate," and the surrounding portion, *a*, *a* (fig. 14), of rammed ganister, which beds on to the main lining of the converter. Figs. 16 and 17 show a fireclay twyer in plan and section; these twyers are made of best fireclay, like an ordinary fire-brick. The bottom or twyer plate is a cast-iron plate with from 12 to 20 holes from 6 inches to 8 inches in diameter, according to the size and number of the twyers. An inverted plan of this with twyers in position, showing lugs holding them, is given in fig. 15.

The holes in the bottom plate are tapered to correspond with the taper on the wide end of the fire-brick twyers, so that these can be placed in the plate only from the bottom side, and cannot be pushed through it. The

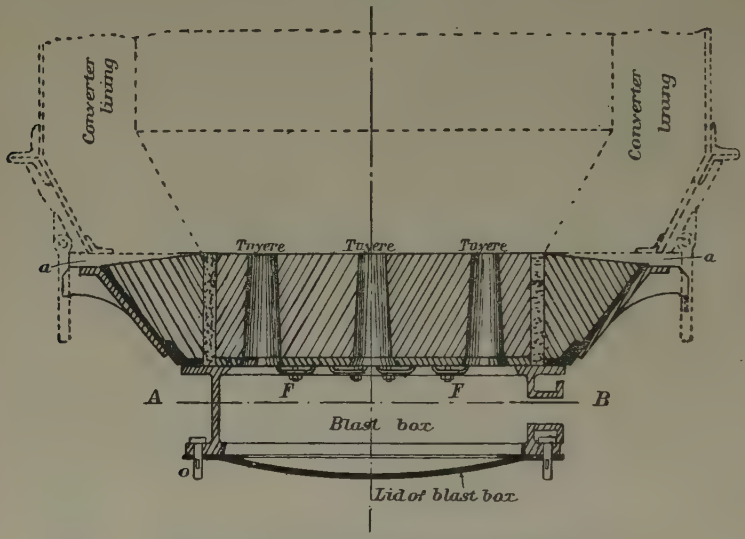


Fig. 14.—Bottom Section showing Twyers.

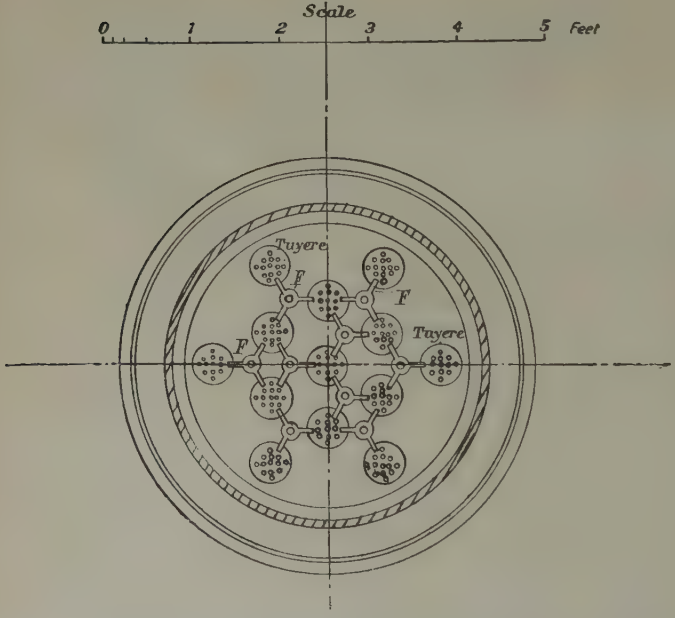
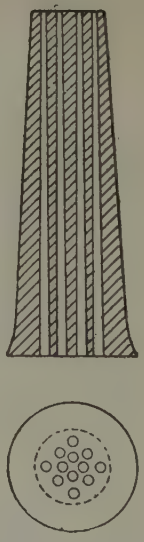


Fig. 15.—Plan of underneath side of Bottom Plate, showing lugs, F, for holding twyer bricks in position.



Figs. 16 and 17.—Twyer Brick for Bottom of Bessemer Converter.

twyers having been inserted in the plate when its under side is uppermost, are fastened in position by claws or lugs, F (fig. 15), held by cotters, screws, or any similar contrivance, none of which must, of course, interfere with the passage of the blast through the twyer holes. The plate is next inverted, and an iron casing, constructed as in fig. 70 (p. 63), or sometimes in two or three sections, is placed round the twyers and fastened to the twyer plate, the spaces round the twyers being rammed up tightly with moist ganister. The "plug" is now ready for drying and baking, and this is usually done in

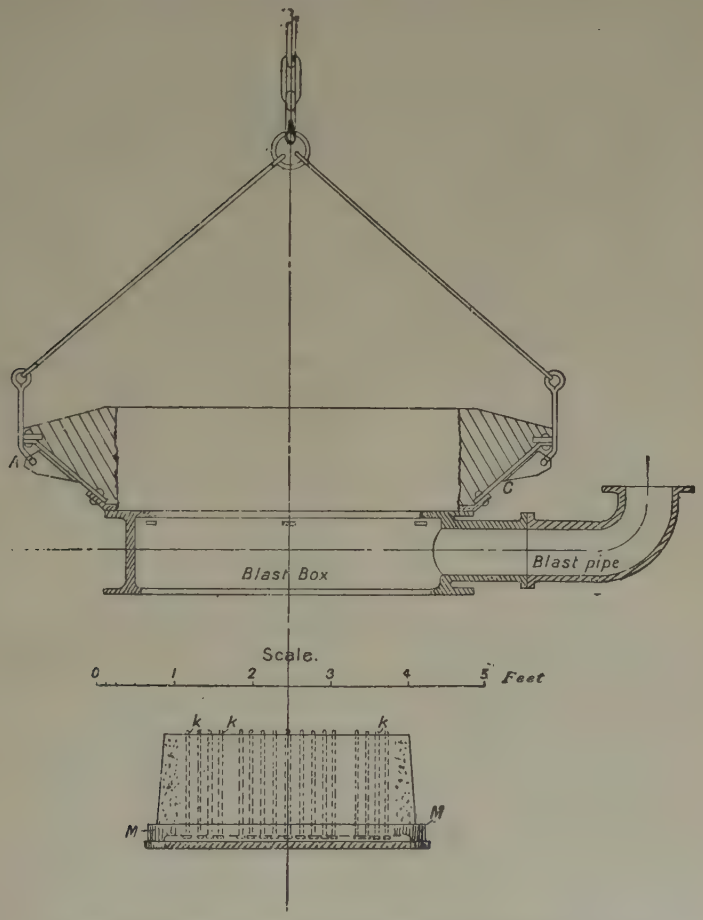


Fig. 18.—Sketch showing method of inserting rammed baked twyer plug in bottom section of the converter.

a special oven, or by means of a gas-heater, and great care must be taken with this operation, as upon this and careful ramming will largely depend its life, and consequently to a considerable extent the output of the converter. The plug may indeed be regarded as the weak spot in the Bessemer plant, for, without apparent reason, a failure may occur at the second or third blow, while at other times, and, apparently under similar conditions, a plug may last 15 or 20 blows, and sometimes more.

At the Barrow Works, instead of using moist ganister, dried ganister mixed with tar is employed, and, it is stated, with better results. Careful drying and baking at a barely visible red heat is required. The plug, having been dried, is drawn on a trolley to a bottom section, from which the old plug has been cut out, and the bottom section is raised by a crane and lowered over the "plug," as shown in fig. 18. In this case a "basic plug" is shown. This will be described later, but the method of fixing the plug is the same in either case. The space "*a*" in fig. 19 between the plug and the ganister lining in the bottom section is now made good by ramming in moist ganister, and the whole bottom section is ready, as shown in fig. 14, for fixing on the converter. It is very important that an air-tight joint should be made between the bottom plate and the top of the blast box at *b* (fig. 19), otherwise the blast will find its way between the two, and force out the ganister ramming at "*a*" between the plug and bottom section; this joint is made by putting a thick daubing of clay round the flange of the bottom plate at *b* before it is in position in the bottom section, and screwing up the set pins, L, very tightly. The weight of the bottom plate is carried by stout pieces of iron which fit into recesses cast in the blast box, and are held up against the bottom plate by set screws, L, as shown.

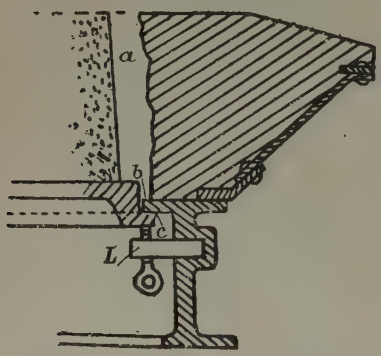


Fig. 19.—Bottom Section, showing method of holding plug in position.

In many Acid Bessemer Works, instead of ramming the plug in an iron casing and drying separately, the old plugs are cut from the bottom section, and a bottom plate with a new set of twyers is put in position, and the whole rammed up with moist ganister. The bottom section and plug are then dried together, but in basic practice the method of making the plug *separately* is always adopted.

Bottom sections are now always made interchangeable, and a number are kept in readiness, so that when one gives out, it can be at once removed and replaced by a new one. The usual method of doing this is to place a trolley on the table of a hydraulic ram, which is generally fixed under each converter, and then to raise the trolley, uncotter the bottom section, lower it by means of the ram, and remove it to the repairing shop. The arrangement for removing and replacing bottom sections is shown in figs. 8, 9, and 10, Plate i.

Replacing a Bottom Section.—In fixing the new bottom it is run on a carriage to the table of the ram, a mixture of fairly wet ganister and fireclay is placed all round the bottom section at *a*, *a* (fig. 10) to form a jointing material, and the bottom is pressed up tightly against the converter by the hydraulic ram and cottered on. The fireclay thus makes a good firm joint, and to make this quite secure, it is generally rammed all round the joint from the outside with small iron rammers. If placed on a vessel already hot from a previous charge of steel, the bottom soon gets sufficiently hot to take another heat, but in the case of a cold vessel, both the vessel and bottom have to be heated with a coal fire previous to blowing.

In some works where there is no hydraulic ram under the converter, the bottom section is hoisted into position and pressed home by powerful screw jacks, and in other cases the vessel is inverted, the bottom hoisted

by an overhead crane, the ring of fireclay and ganister placed round the edge of the converter, and the bottom merely cottered on tightly. The old method of placing the bottom plug in and making the joint from the inside by throwing in balls of ganister through the nose of the vessel, and then ramming with long hammer-headed bars, has been generally discontinued, owing to the loss of time and the risk of bad joints.

Repairing "Plug."—Sometimes it happens that *one* particular twyer in a plug fails or gives way from some unknown cause, and as this will leave a large hole in the plug, before the heat can be finished, there may be considerable risk of the molten metal breaking through the bottom plate. The vessel is then turned upon its side, the blast-box cover removed, the defective twyer cut out, and generally a "dummy" or blind twyer (*i.e.*, a twyer without holes) daubed with ganister inserted, and well rammed round with the same material, or the entire twyer-hole may be completely plugged with ganister.

Materials for Lining.—The life of the lining of the vessel depends upon the composition of the material used, the quality of metal blown, pressure of blast, and rapidity of working, but in well-managed works it should, with occasional repairs, average 600 to 800 blows.

When it can be obtained, the best material to use is good Sheffield, or some similar ganister, which should contain 90 per cent. of Silica, and be practically free from alkalies; in some cases it contains as much as 95 per cent. of Silica. The following may be taken as typical analyses of high-class ganister:—

	Per cent.	Per cent.	Per cent.
Silica	92·05	94·60	95·20
Alumina	2·70	1·40	·59
Oxide Iron	1·85	·90	·74
Lime	0·60	·48	·40
Magnesia	0·20	·16	·16
Alkalies	·20	·14	·18
Water	2·00	2·60	2·70
	99·60	100·28	99·97

In many places where ganister of good quality cannot be procured, excellent results have been obtained by mixing together about 50 to 70 per cent. of finely-crushed quartz rock or old Silica fire-brick, with refractory fire sand, and just sufficient good fireclay to act as a binding material. The whole is ground together, so that the largest pieces are not bigger than hazel nuts, and is thoroughly mixed with just sufficient water to make it plastic.* The twyer bricks are made of best fireclay, Stourbridge fireclay, containing from 60 to 75 per cent. of Silica and from 20 to 35 per cent. of Alumina, being largely used in England. They should be thoroughly kilned. In some cases the lining is cut away by the action of the slag and metal, and in other cases it gathers or thickens owing to some metal and slag setting on the sides and near the bottom of the vessel. These accretions can to some extent be prevented by modifying the composition of the slag by the addition of a little lime or other base to form a double Silicate and more fluid slag. Another plan, where possible, is to blow hotter metal—*i.e.*, metal containing more Silicon—by which the heat is increased, and a more fluid slag obtained. Sometimes an increase in the weight of the charge and more rapid blowing will remove these accumulations, or if this fails coke may be put into the

* Howe, *Metallurgy of Steel*, p. 351.

vessel and blown up; the intense heat thus developed will usually have the desired effect, but if it should not, the only course is to allow the vessel to cool and then chip the lining.

On the other hand, when the lining gets cut away by the action of the slag and metal, it can generally be repaired by throwing balls of ganister through the mouth of the converter to patch the badly worn places; although sometimes it may be necessary to allow the vessel to cool so that the men can get inside to do the necessary repairs.

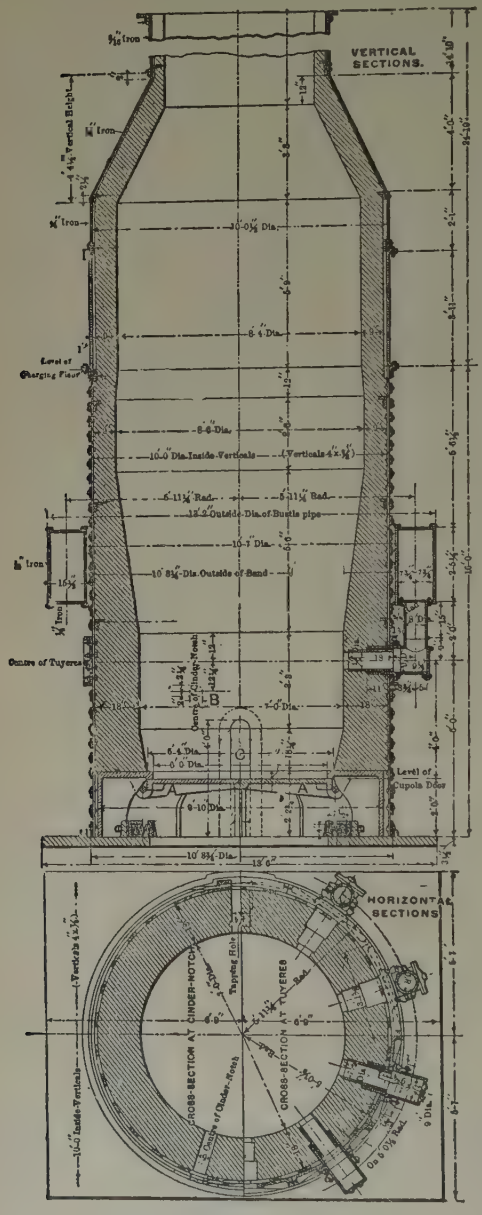


Fig. 20.—Cupola Furnace.

Cupola Furnace.—The molten metal for supplying the converter may either be melted in cupolas, taken direct from the blast furnace, or taken from the latter and passed through a receiver or mixer before finally passing to the vessel.

The modern cupola is really a small blast furnace. In some cases the outside shell will be 10 to 12 feet in diameter, and the blast pressure as much as 2 or 3 lbs. per square inch. It is lined with fire-brick as a backing and then rammed, usually with ganister or some similar silicious material. The height of the cupola platform should be such that when the cupola is "dumped," or raked out, all the debris falls upon the floor level, and ample room should be left to enable the men to readily remove this. Cupolas with drop bottoms are now generally made and found very convenient. Fig. 20 is a sectional plan and elevation of a modern cupola with leading dimensions, and fig. 21 shows the general arrangement of a large cupola working in America, charged by a Wellman charging crane, but the latter is not in use in England for cupola work. A moderate sized cupola, about 6 to 7 feet diameter, outside of

shell, with 5 or 6 twyers and a pressure of blast of 1½ to 2 lbs., will melt 200 to 250 tons of pig-iron per twelve hours.

Position of Cupola.—The position of the cupola in relation to the converters is a matter of considerable importance, and must in the first case depend upon whether it is proposed to tap molten iron direct into the converter by runners, or into a ladle on the same level as the converters, or whether the metal is to be tapped into a ladle on the ground level, and the ladle then raised by a lift or other mechanical appliance and the metal poured into the converter. It may be taken, that in all modern works the latter plan of having cupolas arranged to deliver the molten metal on the ground level is almost universal, and the older plan of tapping direct into the converter, or into a ladle on the converter level, has been discarded. It only remains therefore to select such a position for these furnaces as may be most convenient for receiving the raw material, and for the delivery of the molten metal to the converter platform. This may be either behind or at one end of the converter platform, but should be more or less in a line with the converters, and as near as convenient to the lift.

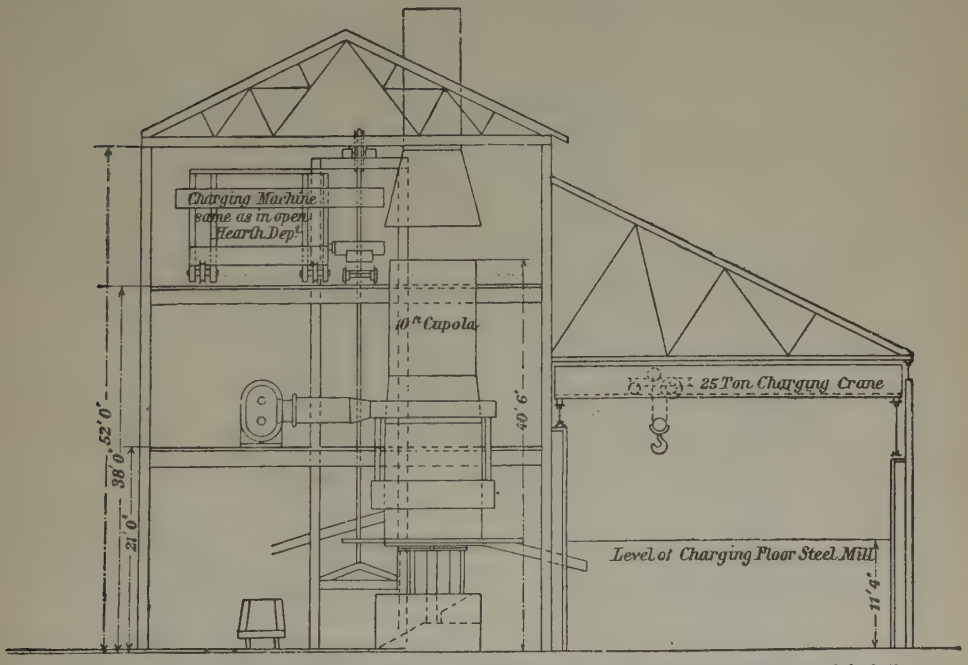


Fig. 21.—Cupola with Wellman Charging Machine. The boxes are taken up on lift full, lifted by machine on cupola platform and emptied into cupola.

The Metal Mixer or Receiver.—From an economic point of view, both as regards labour and fuel, the ideal method is to take molten iron direct from the blast furnace to the converter, and so save the cost of re-melting in a cupola; but owing to the irregularity in composition of such metal, although it has been frequently attempted and in some works is still done, it has been in most cases discontinued. Unless iron of fairly regular composition is used for Bessemer practice, the irregularity in the quality of steel produced, coupled with the decrease in yield, has been found to more

than neutralise the saving in re-melting. It has been found, however, that if runnings or tappings from several blast furnaces can be mixed together, high Silicon or Sulphur in the metal from one furnace is compensated for by low Silicon or Sulphur in the iron from another, and this together with a certain amount of purification, due to chemical action, produces a metal of fairly uniform composition. For some years now it has therefore been the practice to pour the molten blast metal from a number of furnaces

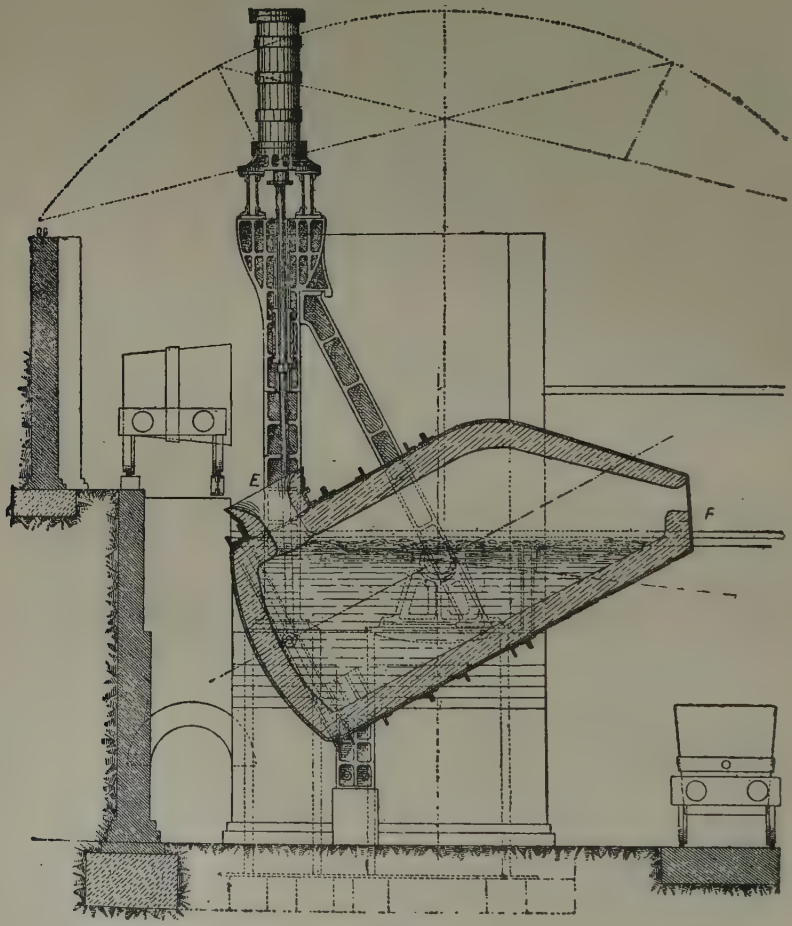
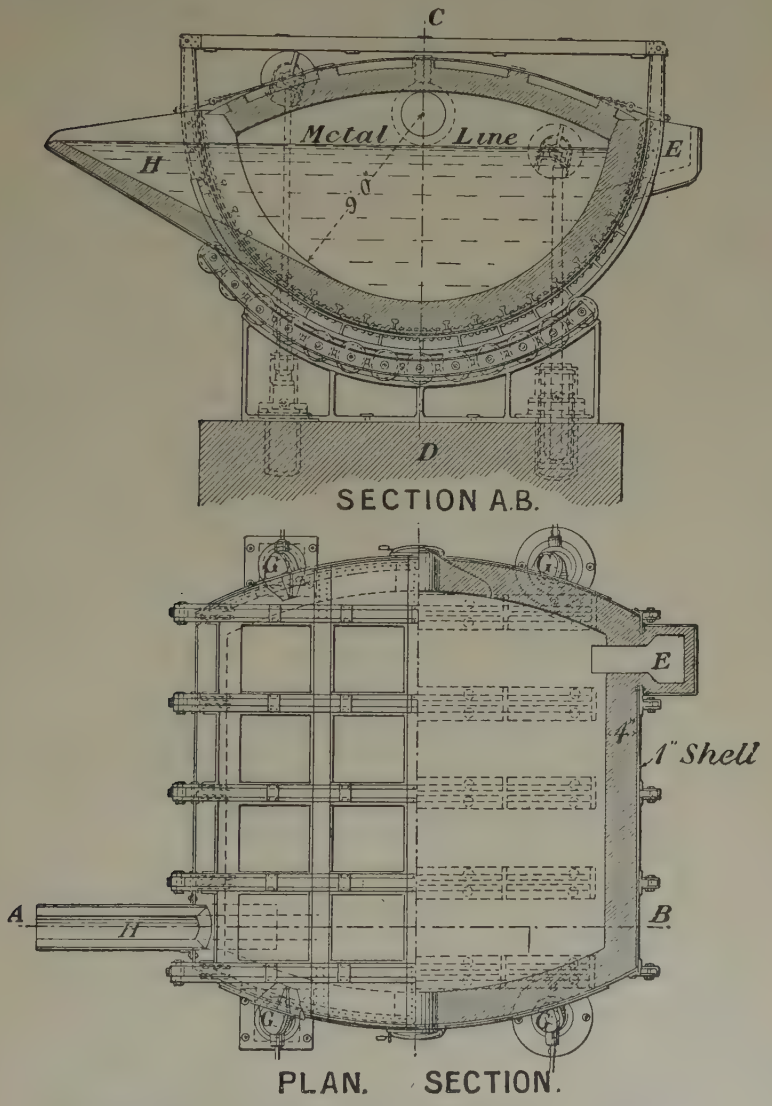


Fig. 22.—150-ton Metal Mixer at North-Eastern Steel Works. It is tilted by a hydraulic cylinder above the mixer. The blast furnace metal is poured in at E and discharged at F into ladle on ground level.

into a large vessel known as a "mixer or receiver." The receivers originally designed were large converter-shaped vessels lined with ganister, and capable of being tilted by powerful mechanical gearing. Fig. 22 shows the 150-ton mixer, erected some years ago at the North-Eastern Steel Works, Middlesbrough, the tilting gear being above, so that in event of the metal breaking out it will not be damaged. The various casts of metal from the blast furnace are transferred in ladles to the mixer, and poured in through

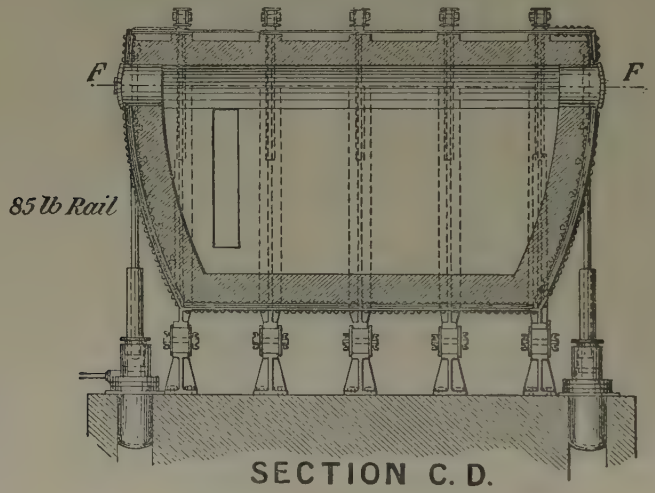
an opening at the top. When the vessel is nearly full, sufficient metal for a "blow" is poured out into another ladle and taken to the converter, additions of blast furnace metal being made to replace that removed from time to time.



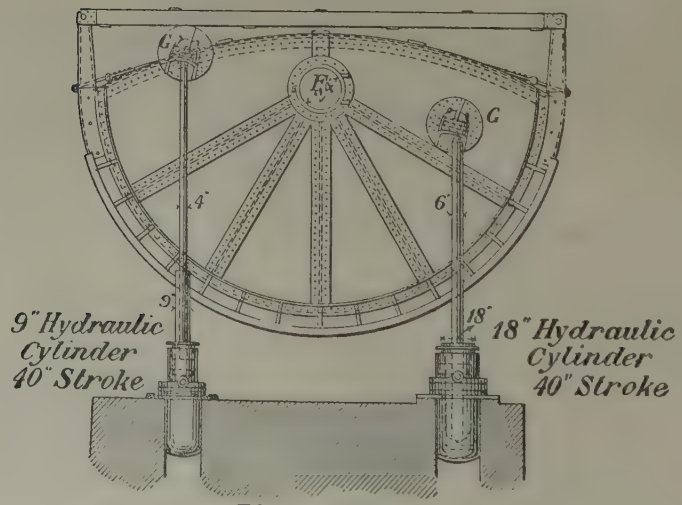
Figs. 23 and 24.—300-ton Metal Mixer—E, Filler; H, pouring spout.

By means of this mixer metals of varying grades, as has been described, can be mixed together, so that a product of fairly uniform composition is obtained. Thus, if a blast furnace is from some accidental cause making white iron—a metal unsuitable for conversion into steel, firstly, on account of the low heat it would yield, and secondly, on account of its high content

of Sulphur—and another blast furnace is making grey silicious iron, then, by mixing the two irons, a product will be obtained suitable for steel-making. It will be hot enough for blowing, and the Sulphur, after an interval, will not, as might be expected, be the mean of the Sulphur percentages of the two metals, but will be reduced, especially if the grey iron is from a blast furnace working a charge containing Manganese.



SECTION C. D.



ELEVATION.

Figs. 25 and 26.

The larger the mixer the better are the results obtained, both with respect to the purification and also in retaining the available heat of the metal. Mixers capable of holding 600 tons of metal are now in use.

Figs. 23, 24, 25, and 26 show the general arrangement of a 300-ton metal mixer in use at the Cambria Iron Company's Works.

The shell is made up of 1-inch steel plates rivetted together, and stiffened by flat bottomed rails. The mixer is lined with fire-brick 18 inches thick. The shell is bound on the outside by 5 cast-steel binders, which rest on roller-bearings, and are continued up at each end, and joined across the top by channels and strap-bolts. The roller-bearings consist of a number of flanged cast-steel rollers, 14 inches in diameter, which are free to move between two cast-steel channels, joined together by distance bolts. The roller-frames are free to move on the heavy cast-iron sole plates, which are circled to form a race for the rollers.

The metal is poured in at the filler, E, and emptied at the spout, H. The mixer is emptied by means of two rams, 18 inches in diameter by 40-inch stroke, and is brought back to the horizontal position by two rams, 9 inches by 40-inch stroke. The rams are attached to the side of the mixer by means of spherical bearings, G. Cleaning and paddling doors are provided at F.

Metals within a reasonable range of composition can be used, but neither very grey (silicious) nor very white (sulphurous) irons can be added in excess without risk of obtaining unsuitable metal for the converter. One important advantage in the use of the mixer is that a reserve of metal is always available, and no time is lost in waiting for the iron to melt down in the cupola. The receiver also admits of the hot metal ladle standing on a weighing machine during pouring, so that the exact quantity of metal wanted may be readily poured into it from the mixer—a condition not so easily fulfilled when the metal is taken from the blast furnace. Charging the receiver is commenced on Sunday night, so that it may be full of metal on Monday morning, and it is found as a matter of experience that it is never advisable to allow the charge of metal to be reduced below one-half the capacity of the mixer until Saturday morning, when it must be gradually reduced prior to emptying. After emptying at each week end the mixer is repaired with ganister, the mouth bricked up, and the charging hole covered and luted with clay, by which means it is kept sufficiently hot to restart on Sunday night.

Mr. Edgar J. Windsor Richards * has given some very complete analyses showing the quantities of iron of varying composition both with regard to Sulphur and Silicon, which can be dealt with in a mixer of fair capacity, and the following results are taken from a table showing removal of Silicon during one month's consecutive working :—

Furnace Metal Charged into Mixer.		Metal taken from the Mixer.	
Composition.	Quantity.	Composition.	Quantity.
Silicon.		Silicon.	
1·25 to 2·00	24·26% of total charge	1·50 to 2·00	3·64% of total charge.
2·25 to 3·00	51·9 ,, ,,	2·25 to 2·75	96·03 ,, ,,
3·25 to 4·00	20·8 ,, ,,	3·00	0·33 ,, ,,
4·25 to 5·00	3·04 ,, ,,	...	No metal above 3% Silicon.

It will thus be seen that although 24 per cent. of the metal charges varied in Silicon from 1·25 to 2·00 per cent., 51 per cent. from 2·25 to 3·0 per cent., 21 per cent. from 3·25 to 4·0, and 3 per cent. from 4 to 5 per cent., yet 96·0 of metal, after passing through the mixer, varied only between 2·25 and 2·75, and only 3·6 per cent. contained less, and practically none exceeded 2·7 per cent. of Silicon.

* *West of Scotland I. and S. Inst. Journal*, 1899.

The removal of Sulphur in the mixer depends largely upon the composition of the metal, the most important constituent apparently being Manganese. Given about 2 per cent. of Manganese in the furnace metal, Sulphur is rapidly eliminated, and a very considerable reduction takes place, provided the Manganese in the bath of the mixer metal does not fall below 1 per cent.

TABLE I.—Analyses showing variations in the Metal before being charged-into, and after being drawn from, the Mixer at Hœrde.

Blow No.	Before Mixing.			After Mixing.		
	Per Cent. of Manganese.	Per Cent. of Silicon.	Per Cent. of Sulphur.	Per Cent. of Manganese.	Per Cent. of Silicon.	Per Cent. of Sulphur.
3932	2·68	·25	·033	2·29	·22	·033
3933	2·86	·34	·055	2·19	·23	·033
3934	2·28	·31	·104	2·54	·27	·041
3935	2·25	·20	·131	2·48	·20	·027
3936	2·23	·35	·050	2·57	·17	·027
3937	1·70	·34	·134	2·34	·20	·033
3938	2·63	·26	·085	2·31	·19	·055
3939	1·93	·20	·074	1·73	·22	·033
3940	2·02	·30	·118	2·43	·18	·038
3941	2·37	·30	·044	2·22	·19	·036
3942	2·37	·17	·074	2·25	·19	·038
3943	2·07	·16	·120	2·22	·19	·036
3944	3·14	·78	·055	2·05	·24	·030
3945	1·93	·17	·071	2·34	·23	·038
3946	2·40	·29	·044	2·25	·51	·044
3965	1·87	·29	·007	2·34	·25	·044
9966	2·34	·29	·107	2·22	·25	·029
3967	2·45	·44	·052	2·10	·31	·038
3968	1·18	·18	·134	2·07	·34	·032
3969	2·68	·37	·137	2·13	·29	·027
3970	2·36	·34	·088	2·07	·28	·022
3971	·89	·21	·160	2·16	·27	·022
3972	2·04	·18	·090	2·10	·31	·027
3973	1·86	·29	·093	1·61	·23	·033
3974	1·37	·40	·047	1·73	·22	·033
3975	1·44	·12	·158	1·76	·22	·030
3976	2·33	·45	·120	1·70	·24	·038

It seems practically certain, from Massenez's * results, that the Sulphur passes into the slag as a Sulphide of Manganese; but whatever the exact reaction may be, the decrease on mixing an iron high in Sulphur with one high in Manganese is undoubted. In Table i. are given analyses of metal from the mixer at Hœrde showing the result of passing manganiferous metal of irregular composition (as regards Sulphur) through the mixer, and further results dealing with irons containing much larger percentages of Sulphur will be found in Massenez's paper referred to above. It will be noticed that the metal from the mixer is very regular in composition, and although frequently the furnace metal contained over 0·100 per cent., and sometimes as much as 0·160 per cent. of Sulphur, in no case did the mixer metal contain more than 0·044 per cent., and it rarely exceeded 0·035 per cent. No doubt the very low Silicon in the metal was favourable to the removal of the

* *Iron and Steel Inst. Journ.*, 1891, vol. ii, p. 76.

Sulphur, and had the former been 1·00 to 2·50 per cent., with the same content of Sulphur, probably the latter would not have been quite so completely removed.

The modern type of metal mixer is similar in general construction to that shown in figs. 23, 24, 25, and 26, but is gas-fired, with or without regeneration; in some cases the air and gas are regenerated, and in other cases the air alone, exactly in the same way as in an open hearth furnace. For basic bessemer or basic open hearth plants, the mixer is usually basic-lined, and the gas firing enables small additions of oxide of iron and lime to be added to form a slag which considerably assists in the removal of Silicon and Sulphur. Under these conditions, in a large mixer Silicon can be reduced from 1·5 to ·5 per cent. or less.

The introduction of the metal mixer marked a very important departure in steel works' practice, and effected considerable saving directly by rendering remelting in the cupola unnecessary, and indirectly by insuring a metal of uniform composition and at a fairly constant temperature. The introduction of the gas fired basic-lined mixer for basic steel works is another step in advance, effecting still further preliminary purification, and thus saving time and decreasing the cost of refractories and repairs in the steel furnace or converter.

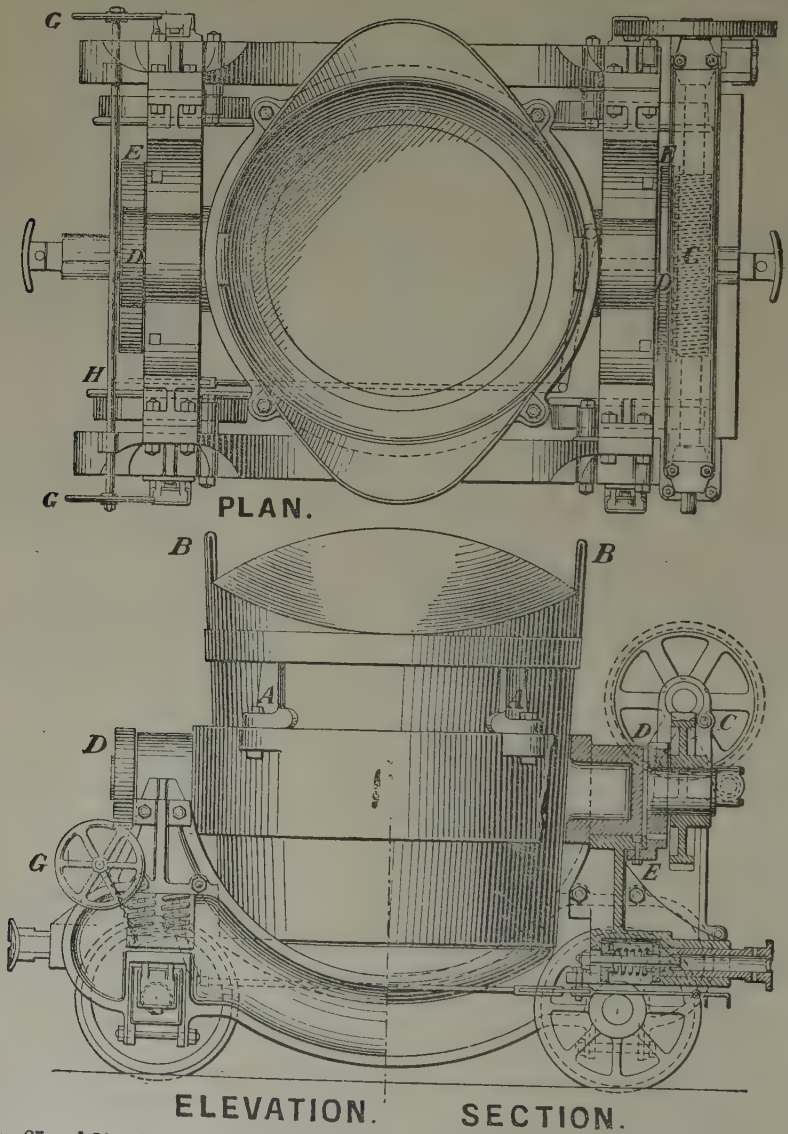
Supply of Metal to Converter.—The molten cast iron may be conveyed to the converter in two principal ways—*i.e.*, either directly from the cupolas by runners, which are simply troughs lined with loam, or other refractory material, and the ends of which enter the mouth of the converters, and are movable; or by first casting from the cupolas, blast furnaces, or mixer into ladles. The former method is now practically obsolete as regards modern practice, and it is therefore necessary to discuss the latter only. The charges of metal are often brought considerable distances in ladles from the blast furnace to the converter or mixer, and may be a considerable time on the road without the occurrence of any inconvenient loss of heat. These ladles are invariably tipping ladles—*i.e.*, the metal is poured from them as from a jug.

Tipping Ladles.—Such ladles are known as direct, or hot-metal ladles—their general features are shown in figs. 27, 28, and 29—and they are specially designed to facilitate pouring the metal and charging the ladle.

It will be seen that the tipping action is effected by a worm and screw motion actuating a trunnion, and one workman can by this gear pour a 10- to 20-ton charge into a converter or mixer without difficulty.

The ladle is held in a cast-iron trunnion belt by means of bolts through brackets, A, on the ladle, and snugs cast on to the trunnion belt. When the ladle requires repairs, the bolts are removed, and it is lifted by lugs, B, and another ladle is dropped into the belt and bolted on. On referring to the drawing, it will be seen that the ladle can be teemed from either side. It is moved forward while it is being turned by the worm and worm-wheel, C., and its forward motion is obtained by means of spur-wheels, "D," which are keyed into the trunnions and geared into the racks E, which are bolted to the end frames of the carriage. To empty the ladle it is moved into position, F, shown in dotted lines in fig. 29. The ladle is provided with a lid lined with fire-brick. The back wheels of the carriage are provided with a brake. By turning the hand-wheels, G, on the front of the carriage a chain coils on to the axle at H, and the brake is brought into action. It will be observed that the carriage is supported on, and the buffers provided with, strong helical springs. The ladle is generally lined with fire-bricks fitting into one another with taper sides, and when these are built in, the whole is covered with a fireclay daubing. This form of ladle can be used either for taking metal direct from the furnace to the mixer or the converter, or from the mixer to the converter.

There are various methods of conveying the ladle to the converter, depending somewhat upon the arrangement of the plant. The plan usually adopted in England is to have an elevated railway track on the platform in front of or behind the converters at about the same level as the trunnions of the converters, and the ladle, with tipping gear attached, as shown in figs. 27, 28, and 29, is run along this until in front of the vessel, when the metal is poured into the converter. At one end, generally near the cupolas,



Figs. 27 and 28.—Hot-metal Ladle—A, Brackets on ladle for securing latter to trunnion belt; B, lifting lugs; C, worm-wheel gearing for turning the ladle; D and E, spur-wheel and rack gearing to give forward motion to ladle during pouring; G, hand-wheel for actuating brake on axle, H.

is a lift which raises the metal ladle to the level of the platform. Instead of being raised by a lift, the hot-metal ladle may be drawn up an inclined plane. Another method is to raise the ladle from its carriage by means of a crane to the mouth of the converter, and while it is suspended by its trunnions, tip the ladle by a chain attached to the bottom.

Another arrangement for tilting the ladle to effect the pouring is that shown in fig. 68, which is in use at the Barrow Works. Here the ladle is tilted by a chain fixed to the bottom and attached to a hydraulic cylinder, while the ladle is supported in the bearing of the carriage. The special point about the ladle is that the trunnions are not fixed centrally on the ladle, but somewhat in front, so that the whole of the metal can be poured into the converter by tilting without moving the ladle forward.

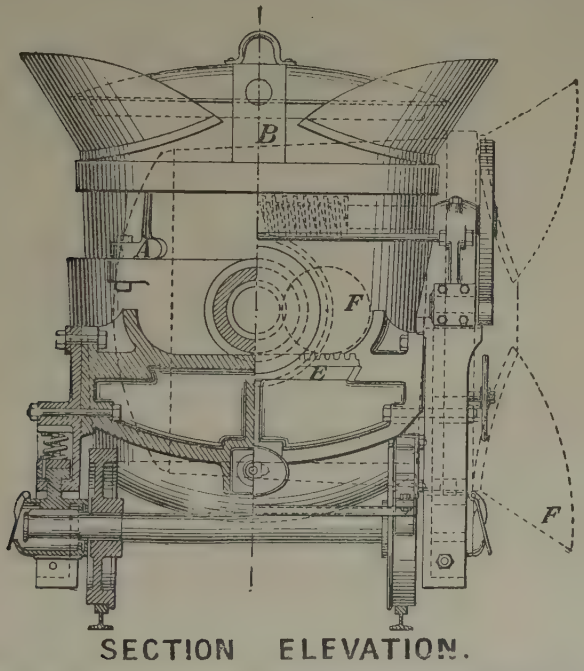
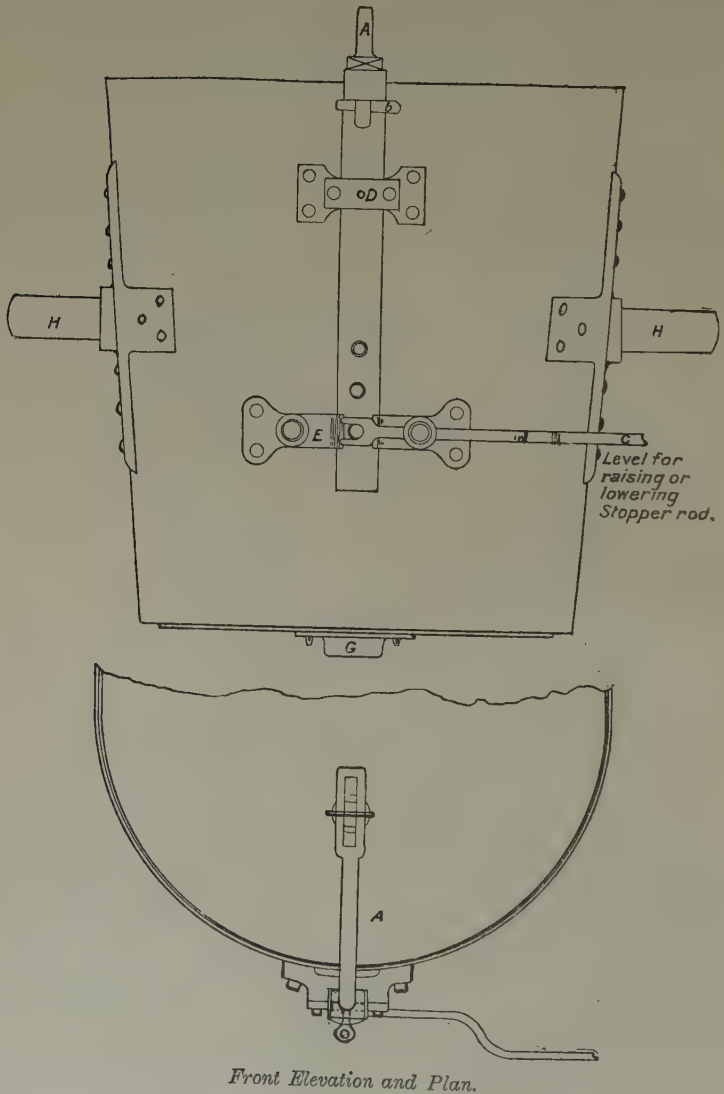


Fig. 29.—The dotted lines show the position of ladle when being emptied.

Blast for the Converter.—The air blast for the converter is supplied by a high-pressure double cylinder blowing engine, usually of the horizontal type, and the pressure of blast will depend upon the size of converter and the head of metal to be overcome. Usually the pressure is about 20 to 25 lbs. to the square inch, and generally a large wrought-iron reservoir is interposed somewhere between the blast engine and the converter to ensure a steady pressure of blast at the twyers of the converters. In a modern engine the blast cylinders will be 58 to 60 inches, or even more, in diameter, but the total twyer area in 20-ton vessels will not exceed 112 square inches, and is generally less, although for rapid blowing the more air forced through in a given time the better. In the new Barrow plant, when first started, they had thirty-three twyers, each containing nineteen holes five-sixteenths of an inch in diameter, and a shallow bath; but although

blows were finished extremely quickly, the metal was so hot as to be unmanageable, and the amount of metal blown out of the converter and wear and tear on linings were so great that the depth of bath had to be increased, and the twyers reduced to twenty-four in number.

The Casting Ladle.—The casting ladle, or the ladle which receives the finished steel for casting into moulds, is shown in figs. 30, 31, and 32, and differs very materially from the "direct metal" ladle. The introduction into the converter of a small amount of slag floating on the metal in the



Front Elevation and Plan.

Fig. 30.—Casting Ladle showing details of arrangement of lever for raising and lowering stopper.—H, Trunnion; D, guide for movable bar carrying goose-neck; A, goose-neck; G, nozzle through which steel is teemed.

direct metal ladle does little harm, but if slag is allowed to pass into the ingot moulds with the steel, the latter is liable to be spoiled, and in consequence the steel cannot be poured from a lip into the moulds, but has to be tapped or teemed from a hole in the bottom of the ladle. For this pur-

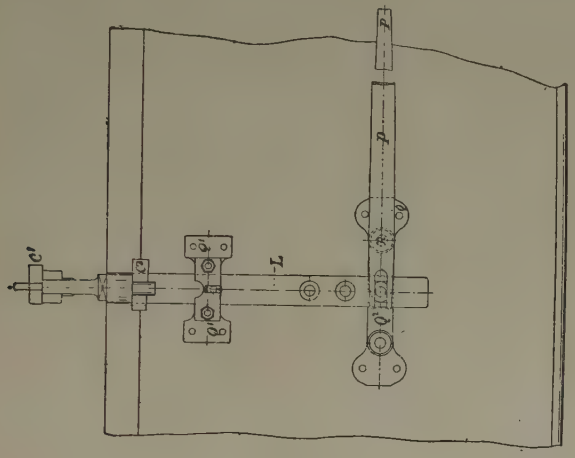


Fig. 32.—As the sliding bar, L, and stopper-rod, B, move together as one piece, previous to teeming the stopper-rod is held rigidly in position by screw, K, and when L is released by unscrewing this, the stopper-rod can be moved freely up and down by means of lever, P.

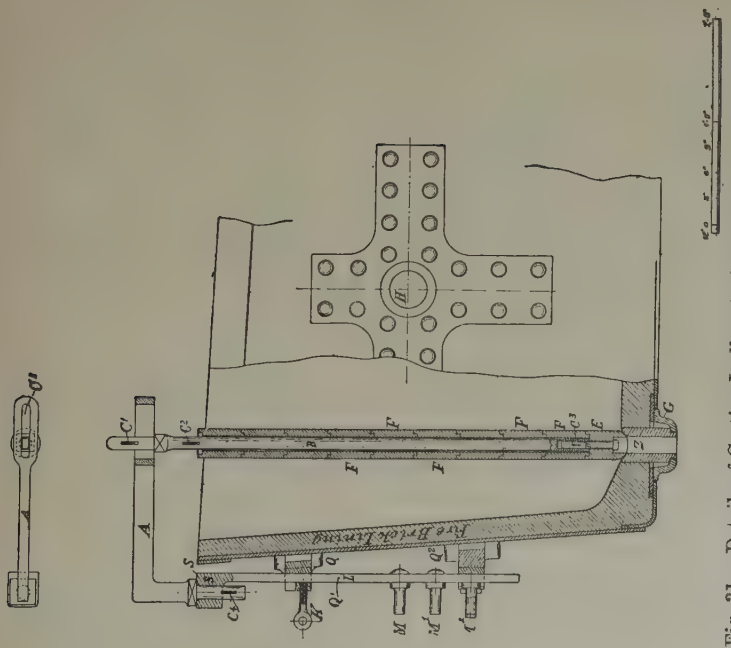


Fig. 31.—Details of Casting Ladle—A, Goose-neck; B, stopper-rod; L, sliding bar carrying gooseneck; M, M^1, M^2, bolts for attaching lever, P; P, lever bar; Q^1, Q^2, brackets on ladle to guide sliding bar, L; K, screw bolt for holding sliding bar rigidly in position previous to teeming; F, fireclay sleeves threaded on steel stopper-rod, B; Z, teeming nozzle; E, fireclay stopper head; G, nozzle box; H, trunnion; C^1, C^2, C^3, C^4, cotter pins; S, forged head on sliding bar through which end of goose-neck is passed, and is fixed by cotter pin C^4.

pose a very simple form of fire-brick valve is used, the general arrangement of which is shown (fig. 31) in position in the ladle. It consists essentially of an iron rod, B, protected from the action of the liquid steel by a series of fire-brick sleeves (fig. 33), which are threaded on the rod, and each sleeve

recesses or dovetails into its neighbour. The bottom sleeve, known as the stopper-head (fig. 34), has practically a spherical end, which fits into a hollow cup-shaped brick built into the bottom of the ladle as shown at Z (fig. 31). This forms the valve seat, and is known as the nozzle. The stopper-head and nozzle (fig. 34) being practically similar surfaces, when the stopper is fixed down firmly into the latter, and a little sand sprinkled round, a metal-tight joint is formed, and no metal can pass from the ladle; but on raising the stopper rod, B, by means of the lever shown, the molten

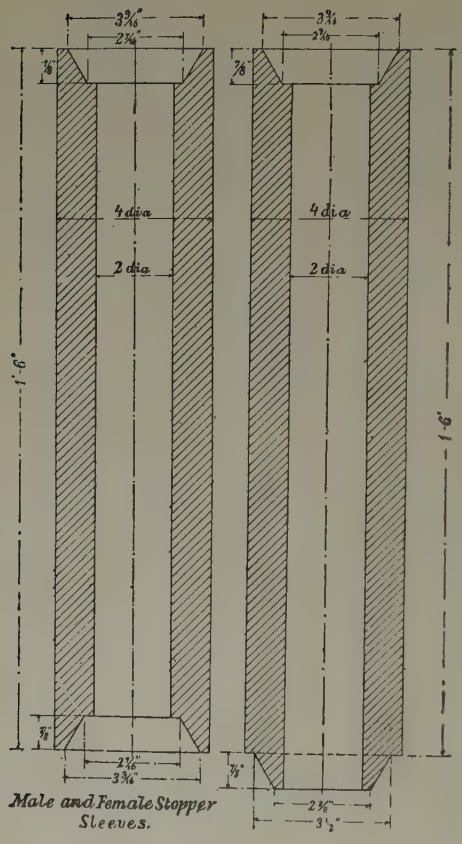


Fig. 33.

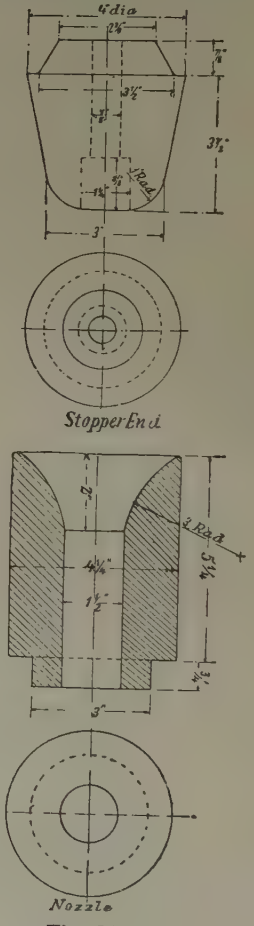


Fig. 34.

steel flows freely through Z, and can be received in an ingot mould placed underneath. The stopper-head is fixed on to the rod, B, by an iron or steel bolt with a forged head at one end to fit in the recess at the bottom of the brick, and the other end of this bolt fits into the end of the iron rod, B, (fig. 31), which is bored out to receive it, and a cotter pin, C^3, hammered in and bent over rigidly connects the two. The bottom recess in the stopper-head, which is not completely filled with the bolt head, is rammed up with stiff fireclay, and the whole dipped in clay wash, previous to fixing on the

rod, B. The sleeves shown in fig. 33 are also dipped in clay-wash, and threaded on B from the top end of the rod until the rod is covered, when they are held rigidly together by means of an iron collar and cotter pin, C^2.

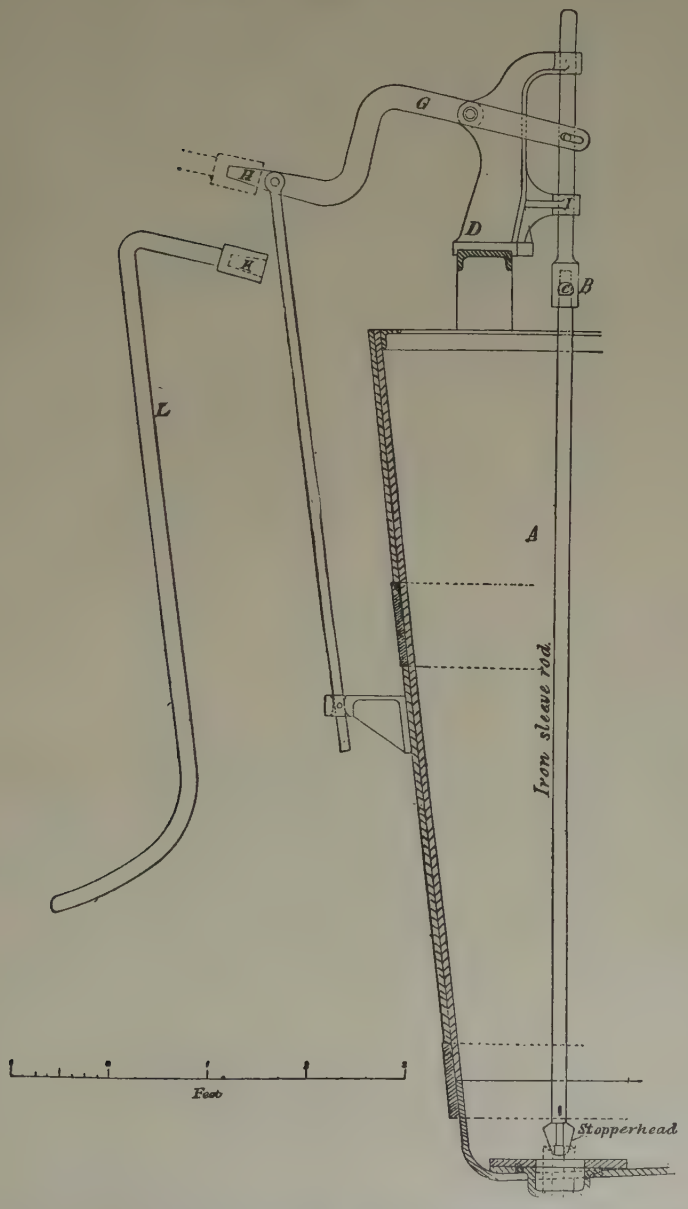


Fig. 35.—Details of 40-ton Casting Ladle—A, Stopper-rod ; B, socket for receiving end of stopper rod ; D, bracket for holding and guiding stopper-rods; G, lever for raising or lowering stopper-rod ; L, movable lever bar which fits on lever G at H.

The whole rod is then well daubed with and dipped in clay-wash, to make all the joints between the sleeves perfectly close so that no metal can get between them. Great care is necessary when threading the sleeves on the rod to see that each joint is well dovetailed into its neighbour. When finished, the stopper-rod is carefully dried, and is then ready for fixing into the goose-neck, A, by passing the top end through the slot in this bar, and firmly cottering it by means of cotter pin, C^1.

The nozzle is usually fixed in the bottom of the ladle, a few inches from the front side, and the slot in the goose-neck, A, allows of reasonable adjustments either nearer or further away from the front side of the ladle. The careful adjustment of the stopper-rod, so that it will work easily and yet truly into the nozzle, is one of the most important practical details in a steel-melting shop. If this is not most carefully attended to, a leaky joint at the valve seat is the result, and the metal slowly trickles through, and rapidly cuts away the nozzle; or if the metal is at all cold, it may solidify round the stopper-end. In the latter case, it may be impossible to teem the metal at all, and in the former what is known as a running stopper will result, and half the metal may be lost in the casting pit before it can be got into the ingot moulds.

Fig. 30 shows an excellent design for a 10-ton ladle, used by Mr. Joseph Colley at Messrs. Hickman's works, which combines rigidity with simplicity; with care there should be little risk of trouble with such an arrangement, as the stopper can be raised and lowered easily by the lever so that the stream of metal passing through Z is well under control. Fig. 35 shows another arrangement of lever for operating the stopper-rod, which has given excellent results with a large 40-ton ladle. The ladle itself is generally lined with special fire-bricks $1\frac{1}{2}$ to 2 inches thick, and afterwards daubed with ganister, Stourbridge bricks being those usually employed in this country. Care must be taken to dry the ladle thoroughly before use.

In some English works the ladles are lined with a mixture of loam, sand, and ganister, the bottom being rammed ganister, but in America at many works, according to Mr. Howe,* loam or moulding sand is used alone.

After the teeming of each heat, the goose-neck, A, and the stopper-rod, B (fig. 31), are removed, the ladle turned over, the slag poured and afterwards chipped out if necessary, and the nozzle carefully cleaned and reformed by ramming a little loam sand round it, and coating it with fireclay-wash. Great care must be taken not to leave any loose sand on the sides where the stopper-head has to bear, otherwise a running stopper will result. The goose-neck is then replaced in S (fig. 31), a new stopper-rod is fixed into the goose-neck by a cotter, C^1, as before, and the ladle is ready to receive another heat.

The Casting Crane.—The casting ladle is usually carried upon a centre crane known as the casting crane, and this is one of the most important mechanical appliances in a Bessemer plant, especially in these days of large charges and rapid work. In fig. 36 is shown a 15-ton hydraulic casting crane, designed by Messrs. Tannett, Walker & Co., Ltd. It consists of a large hydraulic ram, to which is attached a radial arm or jib which carries the casting ladle. The crane must have at least three motions—(1) a vertical motion up and down to enable the ladle to be brought close under the nose of the converter, and to be able to clear ingot moulds of different heights; (2) a horizontal motion for a few feet along the jib of the crane, so that it can accommodate itself to the converter as it tilts over more or less; and (3) it must move round horizontally with as large a radius as possible, so that

* Howe, *Metallurgy of Steel*, p. 359.

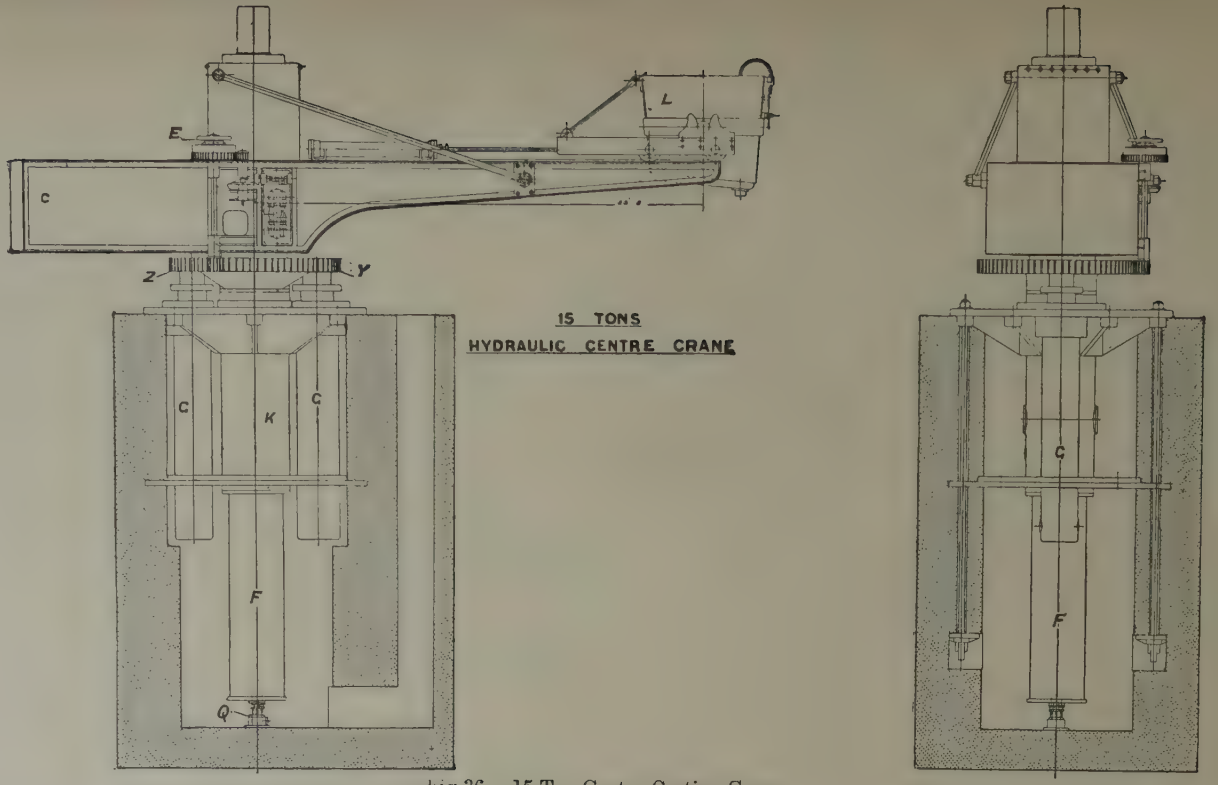


Fig 36.—15-Ton Centre Casting Crane.

The actual lifting is done by two lifting cylinders, G G, the ram, F, acting as a guide and post for withstanding the stress of the load, sliding up and down in a strong foundation casting, K, capable of carrying the whole weight of crane. At the top of F is a crosshead, Y, firmly attached to it with teeth cast on its circumference into which gears the turning pinion, Z. The rotation is done by the small hydraulic reversing engine through gearing to Z, the wheel, E, being a friction clutch to couple up the gearing. The water goes in and out at the telescope tubes shown at Q. At C there is a balance weight to balance partially weight of ladle, L, when full of metal. The water is admitted into the lifting cylinders, G G, at the top of each cylinder, so that when the crane lowers, each cylinder is left full of water in the clearance space.

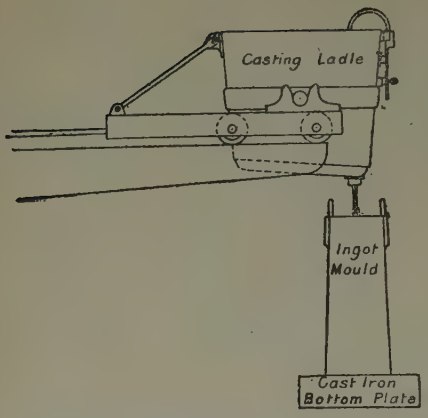


Fig. 37.—Ingot Mould standing on Cast-Iron Plate, with steel being teemed into it from Casting Ladle.

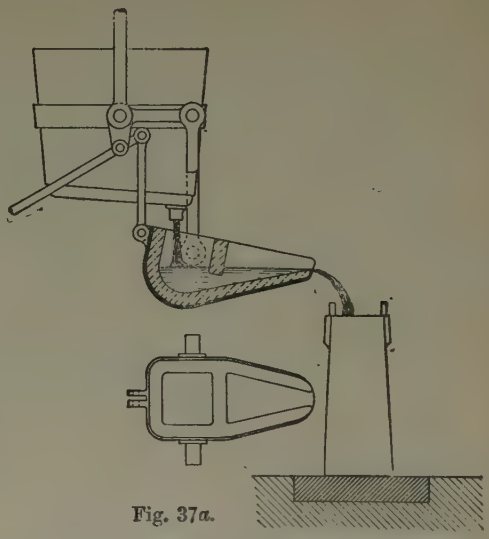


Fig. 37a.

it may cover a large number of ingot moulds standing at the circumference of the pit. The crane shown fulfils all these conditions, besides being admirably designed for strength, and for the ease with which it can be manipulated. The details will be readily understood from the sketch and description. Many modern centre cranes are top-supported, but the one shown is not, and the advantages and disadvantages of the two types are engineering questions which we have not space to discuss here.

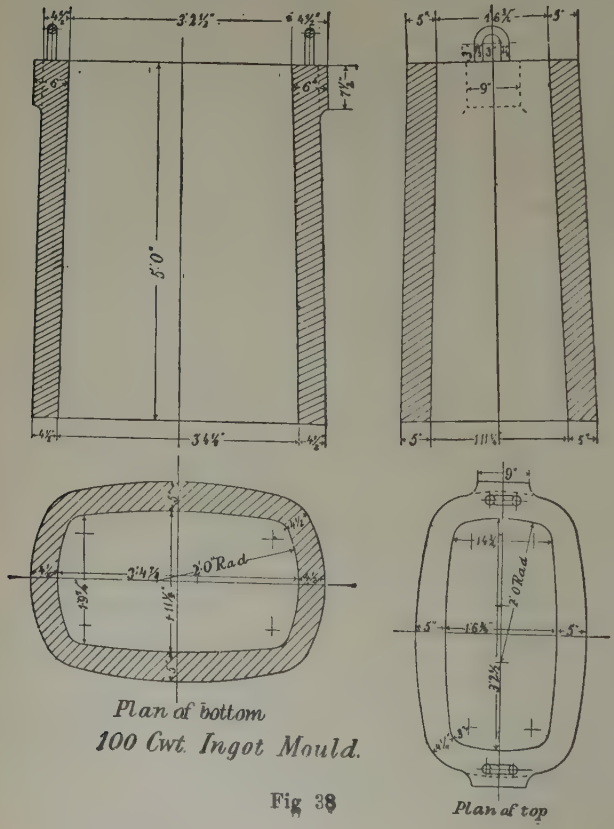


Fig 38

Ingot Moulds.—The fluid metal from the casting ladle is teemed into cast-iron moulds or shapes, which may be of almost any convenient form and size, these being determined by the purpose for which the steel is required. Thus, we may have ingot moulds square, circular, oval, flat, octagonal, &c., in horizontal section, but

generally the section is rectangular, with rounded corners and just sufficient taper to allow the mould to be easily drawn off when the ingots are set. The moulds should always be made of grey hematite pig, and when ready to receive the steel should stand on thick cast-iron plates known as bottom plates (see fig. 37). The intensely hot steel has a tendency to cut these bottom plates away rapidly; but their life may be somewhat prolonged by putting a small piece of thin scrap steel plate on the centre of each bottom before casting.

When the metal is teemed direct in this way it falls into the ingot mould with considerable force, especially when the ladle is a large one, and contains a considerable weight of metal; splashing up the sides of the ingot mould is then liable to occur, and cause surface defects on the ingot, which may or may not roll or forge out during subsequent treatment. A device to mitigate this trouble is shown in fig. 37*a*, by which the metal is first teemed into a vessel attached to the ladle and allowed to overflow into the moulds from a spout.

In figs. 38, 39, 40, and 41 are given sketches of ingot moulds of different shapes. The dimensions of ingot moulds for different weights of ingots are given (Tables ii., iii., and iv.) for reference. The letters on the sketches correspond to those in the different tables; thus, A and B, Table ii., give the width and breadth of the bottom of the mould, C and D the same at the top, while O gives the depth of the mould, and E F G H I the thickness of the metal walls in the positions indicated.

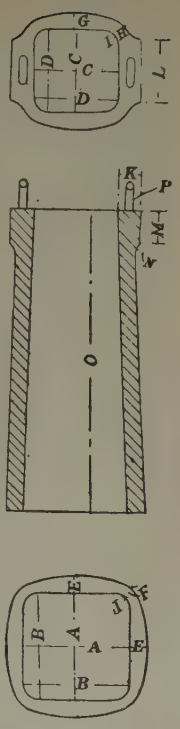


Fig. 39. — Square Ingot Moulds, with dimensions.

TABLE II.—Sizes in Inches (Fig. 39).

Weight of Ingot.	A	B	C	D	E	F	G	H	I	K	L	M	N	O	P
7 cwts.	8¾	8½	7¼	7	2¾	2½	2¼	1¾	1¼	3¼	7	5¼	5	55	1
15 ,,	10	9¾	8½	8¼	3	2½	2½	2	1¾	4	8½	6	...	72	1½
19 ,,	13¾	13½	11¾	11½	3	2½	2¼	2	1¼	3½	8	6	5	56	1¼
20 ,,	14	13¾	12½	12¼	4	3¾	3¾	3½	2	5¼	10	5	...	54½	1½
20 ,,	14½	14¼	12¾	12½	3¾	3¼	3	2½	2	4¼	9	6	...	54	1½
22½ ,,	14¼	14	12¾	12½	3	2½	2¼	2	1¼	3½	7½	6	5	57	1¼
26 ,,	11½	11¼	9½	9¼	3½	3	3	2½	1¾	4	9	6	...	72	1½
26 ,,	15½	15¼	13¾	13½	4⅛	3¾	3⅜	3¼	2	4¼	9	6	...	57	1½
26 ,,	15½	...	13½	...	3½	...	3½	3	2	4	...	6	...	66	1½
32 ,,	14½	14¼	12¾	12½	3¾	3¼	3¼	2¾	2	4¼	9	6	...	66	1½
42 ,,	20	19¾	18½	18¼	4½	4	3½	3	1½	5½	11	6	...	54	1⅝
23 ,,	13¾	...	11½	...	3	...	2½	...	1½	3	6	5	...	65	1¼
36 ,,	15½	...	13½	...	2¾	...	2½	...	2	3¼	8	4	...	72	1⅜

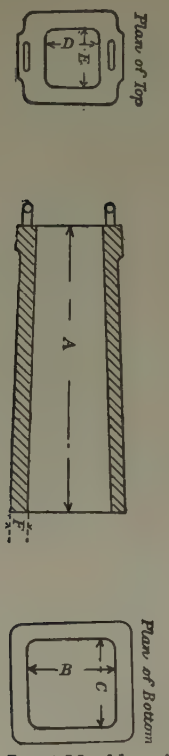


Fig. 40.—Square Ingot Moulds, with dimensions.

TABLE III.—Sizes in Inches (Fig. 40).

Shape.	A	B	C	D	E	F	Weight of Ingot Moulds.		
	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Cwts.	Qrs.	Lbs.
Square, - - -	63	13¼	...	10⅜	...	3		...	
,, - - -	64	13¼	...	10⅜	...	3	21	2	20
,, - - -	65	13¾	...	11½	...	3	21	2	0
,, - - -	60	12	...	11	...	4	28	0	14
,, - - -	54	10	...	7⅜	...	2¾		...	
,, - - -	45	9	...	7⅛	...	2¾		...	
Oblong, - - -	44	27	16	25	14	4½	35	0	0
,, - - -	43	25½	15	23½	12	4½	33	0	0
Quadruple group mould	32	6	...	5¼	...	1¾	15	0	0
,, ,,	32	7	...	6¼	...	2	17	3	0
,, ,,	40	8	...	7¼	...	2½	29	2	0
Square, - - -	64	13	...	10⅛	...	3	19	3	0
,, - - -	48	14¼	...	12¼	...	4	24	1	14
,, - - -	48	14¼	...	12¼	...	3		...	
Solid end, - - -	66	10¼	...	8⅝	...	2¾	19	2	0
Oblong, - - -	73	31	21	27½	18	4½	70	0	0
,, - - -	65	32½	19	29½	16	4	55	1	0
Square, - - -	56	11½	...	9½	...	3	16	2	0
Oblong, - - -	51½	29½	20	27	18¼	4½	47	1	0
Square, - - -	54	15¼	...	14	...	3¼	24	2	14
,, - - -	66	14	...	12	...	3		...	

TABLE III.—*Continued.*

Shape.	A	B	C	D	E	F	Weight of Ingot Moulds.		
	Inches.	Inches.	Inches.	Inches.	Inches.	Inches.	Cwts.	Qrs.	Lbs.
Square,	66	15	...	13	...	$3\frac{1}{2}$		...	
,,	60	16	...	14	...	$3\frac{1}{2}$		...	
Oblong,	84	36	$22\frac{1}{2}$	$32\frac{1}{2}$	$18\frac{1}{2}$	$3\frac{3}{4}$	75	0	0
,,	72	24	20	22	18	$4\frac{1}{2}$	60	0	0
,,	66	$30\frac{1}{2}$	$17\frac{3}{4}$	$29\frac{1}{2}$	$16\frac{3}{4}$	$3\frac{1}{2}$	52	0	0
Square,	66	$15\frac{1}{2}$	...	$13\frac{11}{16}$	...	$2\frac{3}{4}$		...	
,,	66	$16\frac{1}{2}$	...	$14\frac{1}{2}$	...	$3\frac{3}{4}$		...	
,,	82	$18\frac{1}{2}$	...	$16\frac{1}{2}$	...	4		...	
,,	78	$18\frac{1}{2}$	...	$16\frac{1}{2}$	...	4		...	
,,	46	$11\frac{1}{4}$	...	10	...	3	14	1	0
Oblong,	66	$30\frac{1}{2}$	$18\frac{1}{2}$	$29\frac{1}{2}$	$16\frac{3}{4}$	$3\frac{1}{2}$	52	1	0
,,	66	20	17	18	15	$3\frac{1}{2}$		...	
Square,	66	18	...	16	...	$3\frac{1}{2}$	52	1	0
Oblong,	$67\frac{1}{2}$	$32\frac{1}{2}$	25	$29\frac{1}{2}$	$22\frac{3}{4}$	5		...	
Square,	69	$13\frac{3}{4}$	...	$11\frac{1}{4}$	...	3	23	0	0
Oblong.	84	$28\frac{1}{4}$	$18\frac{1}{2}$	$26\frac{1}{4}$	$16\frac{1}{4}$	$4\frac{1}{8}$	61	2	0
Square,	60	17	...	15	...	$3\frac{1}{2}$		...	
Oblong,	75	28	$18\frac{1}{4}$	$26\frac{1}{4}$	$16\frac{1}{4}$	4		...	
Square,	48	12	...	$10\frac{1}{2}$	...	3		...	
,,	66	$12\frac{1}{2}$	...	10	...	$2\frac{1}{4}$		...	
Oblong,	54	19	$12\frac{1}{4}$	18	$10\frac{3}{4}$	3	22	2	0
Square,	$67\frac{1}{2}$	14	...	$11\frac{3}{4}$	...	3	22	0	0
,,	66	$10\frac{1}{4}$	...	$8\frac{5}{8}$	...	$2\frac{3}{4}$	18	1	0
,,	66	17	...	15	...	$3\frac{1}{2}$		...	
,,	66	18	...	16	...	$3\frac{3}{8}$		...	
Oblong,	72	18	15	20	17	$3\frac{1}{2}$		...	
Square,	72	$14\frac{1}{2}$	...	12	...	$2\frac{7}{8}$		...	
,,	72	17	...	$14\frac{3}{4}$	...	$3 \times 3\frac{1}{2}$		...	
,,	72	17	...	15	...	$3\frac{3}{4}$		...	
,,	66	$18\frac{1}{4}$	...	$16\frac{1}{2}$	...	$3\frac{3}{4}$		...	
,,	66	16	...	14	...	$3\frac{1}{2}$		...	
,,	72	14	...	12	...	3		...	
,,	72	$12\frac{1}{2}$	...	10	...	$2\frac{1}{4}$		...	
Octagon,	48	17	...	17	...	$4\frac{3}{8}$	1	10	1
,,	72	$18\frac{1}{4}$	...	$18\frac{1}{4}$	...	$5\frac{3}{8}$	2	19	0
Square,	64	$10\frac{1}{2}$	...	$9\frac{1}{2}$	...	3	0	19	1
Oblong,	54	$15\frac{1}{2}$	$12\frac{1}{2}$	$14\frac{1}{2}$	$11\frac{1}{2}$	3		...	
,,	45	$15\frac{1}{2}$	$12\frac{1}{2}$	$14\frac{1}{2}$	$11\frac{1}{2}$	3		...	
Square,	60	14	...	12	...	3	Closed top.		
Group,	32	6	...	$5\frac{1}{2}$	...	$1\frac{3}{4}$	,,		
Oblong,	60	$40\frac{7}{8}$	$23\frac{1}{4}$	$38\frac{1}{2}$	$18\frac{3}{4}$	$4\frac{1}{2} \times 5$	,,		
Square,	72	13	...	$10\frac{1}{2}$	...	3	,,		
Oblong,	72	36	$22\frac{1}{2}$	$32\frac{1}{2}$	$18\frac{1}{2}$	...	Semi-closed.		
Square,	72	17	...	$14\frac{3}{4}$	...	$3 \times 3\frac{1}{2}$	...		
,,	72	16	...	14	...	$3\frac{1}{2}$	...		
,,	66	17	...	$14\frac{3}{4}$	...	$3 \times 3\frac{1}{2}$	...		
,,	$76\frac{1}{2}$	$14\frac{1}{8}$	...	$11\frac{5}{8}$	...	3	...		
,,	72	18	...	16	...	$3\frac{3}{8}$	. .		
,,	$65\frac{1}{2}$	13	...	$10\frac{1}{2}$	...	3	...		
,,	63	17	...	$14\frac{3}{4}$	...	...	...		
Oblong,	60	$40\frac{7}{8}$	$23\frac{1}{4}$	$38\frac{1}{2}$	$18\frac{3}{4}$	$4\frac{1}{2} \times 5$	...		
Square,	60	$11\frac{3}{4}$	$11\frac{3}{4}$	$9\frac{1}{2}$	$9\frac{1}{2}$	3	...		
Oblong,	33	6×5	$11\frac{1}{2}$	$5\frac{1}{4} \times 4\frac{1}{4}$	$10\frac{3}{4}$	$2\frac{3}{8}$	...		
,,	33	$4\frac{1}{2}$	$10\frac{1}{2}$	$3\frac{3}{4}$	$9\frac{3}{4}$	$2\frac{1}{2}$	...		
,,	72	36	$22\frac{1}{2}$	$32\frac{1}{2}$	$18\frac{1}{2}$	...	Open top.		
Square,	72	$15\frac{1}{2}$	...	$13\frac{1}{2}$	...	$2\frac{3}{4}$	...		
,,	72	15	...	13	...	$3\frac{1}{4}$	...		
Oblong,	60	$52\frac{3}{8}$	$22\frac{3}{4}$	50	$18\frac{1}{4}$	$6 \times 5\frac{1}{2}$	Open top.		
,,	78	$34\frac{1}{2}$	$21\frac{1}{2}$	$31\frac{1}{2}$	$18\frac{1}{2}$	$3\frac{3}{4}$	Contracted top.		

TABLE IV.—Sizes in Inches (Fig. 41).

Weight of Ingot.	A	A¹	B	B¹	C	C¹	D	D¹	E	E¹	F	G	G¹	H	I	K	L	M	O	P
26½ cwts. - -	18½	12	18⅜	11⅞	16	10½	15⅞	10⅜	2½	3	2	2½	2¼	2	1½	3½	8	5	57	1½
29 ,, - - -	18½	15	18¼	14¾	16½	13	16¼	12¾	5¼	5¼	4¾	5	5	...	2	6½	11	6	54	2
30 ,, - - -	21	18	...	...	19½	16½	...	...	4¼	4¼	4	4¼	4¼	4	...	5	10	6	44	1½
30 ,, - - -	14	13	13¾	12¾	12	11	11¾	10¾	3¾	3¾	3¼	3	3	2¾	1¾	4¼	8½	6	66	1½
33 ,, - - -	19¼	15¼	19	15	16¾	12¾	16½	12½	3	3¾	2¾	3	2¾	2⅜	2¼	4¼	10	6	57	1½
35 ,, - - -	19	15	...	...	17	13	...	...	3¾	3¾	3¼	3¾	3¾	3¼	2	4	...	6	66	1½
40 ,, - - -	18	14½	17¾	14¼	16	13	15¾	12¾	4	4	3½	3½	3½	3	2	4½	8½	6	72	1½
45 ,, - - -	24½	17	22½	15	22	14	19½	12	4⅜	4½	...	4⅝	4½	...	...	...	...	...	56	1⅝
45 ,, - - -	23½	18½	23¼	18¼	22	17	21¾	16¾	5	5	4¼	4	4	3½	1½	5½	11	6	54	1⅝
52 ,, - - -	24	17	23¾	16¾	22	16	21¾	15¾	4	4	3½	3½	3½	3	2	4½	8½	6	72	1½
65 ,, - - -	26	19	25¾	18¾	23½	17¼	2 3¼	17	4¼	4½	4¼	4	4¼	4	3	6½	11	6	73	1¾
70 ,, - - -	30½	19	29	18	27½	16	...	...	4	4¼	3½	4	4¼	3½	2½	5	...	8½	65	1⅝
72 ,, - - -	32⅝	18	...	17½	30	16¼	...	...	4½	5	4¼	4	4½	...	3	6¼	11	6	67	2
75 ,, - - -	32½	19	30	18	29½	16	27	15	4	4¼	3½	4	4	3½	2½	5	...	8½	65	1⅝
80 ,, - - -	30	17	29¾	16¾	28	16	27¾	15¾	4½	4¾	4¼	4¼	4¼	3¼	2½	5½	8½	6	72	1½
80 ,, - - -	32½	21	32¼	20½	30½	19½	30	18	4½	4¾	3¾	4½	4	3½	3	5½	...	...	60	...
95 ,, - - -	36	22	33½	20	33	19	30½	17	4½	5	4	4	4½	3½	1½	5	...	8½	65	1⅝
35 ,, - - -	22½	15½	22⅝	15⅝	20	13	19⅞	12⅞	3	3½	2¾	3	3	2½	2½	4¼	10	6	54	1½

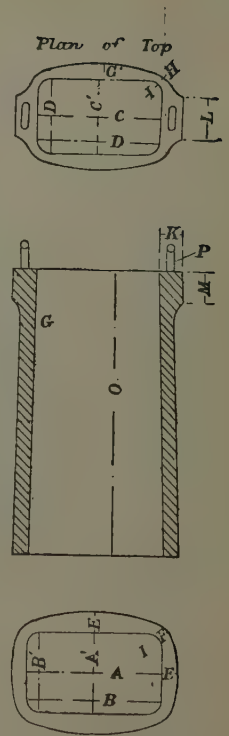


Fig. 41.—Slab Ingot Mould.

As the cost of ingot moulds amounts, in the aggregate, to a considerable sum in a large works, it is of the greatest importance that they should have as long a life as possible. To ensure this, they must be made from high quality grey hematite pig-iron, the presence of comparatively small amounts of Phosphorus causing them to crack, &c.

Apart from the extra cost directly involved, the loss of time due to a bad set of moulds causing ingots to stick, &c., is an important matter, and may seriously interfere with the output of the plant. For ordinary Bessemer or Siemens steel an ingot mould should stand from 60 to 70 casts, but frequently they do not average more than 50 and sometimes less, while, on the other hand, 100 casts are sometimes obtained.

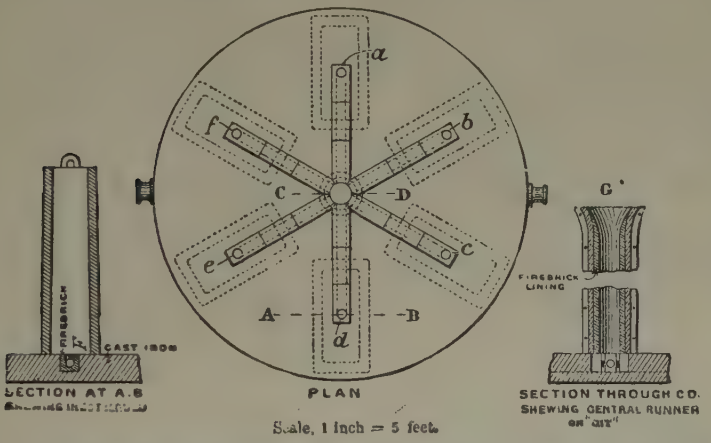


Fig. 42.—Cast-Iron Plate for Bottom Casting, showing "git" and moulds in position. The metal is teemed from the ladle down the "git," G, and flows along the six fire-clay pipes, built up of runner-bricks, when it enters the centre of the ingot mould through the holes in top of the runner-bricks, marked *a*, *b*, *c*, *d*, *e*, *f*, and rises until the moulds are full.

Moderate sized ingots from, say, 10 inches square and upwards are generally cast from the top as above described, but sometimes bottom casting is employed, more especially when a large number of small ingots are required. In bottom or group casting the moulds are closed at the top, but have small ventholes for the air to escape, and, instead of each ingot mould standing upon a separate bottom plate, one large bottom plate is used on which from 4 to 12 ingots may be cast according to size. In these bottom plates are cast grooves in which runner-bricks can be placed, these bricks being really fireclay pipes for the metal to run through. The runner-brick which comes under each ingot has a central hole about $1\frac{1}{2}$ inches diameter for metal to pass up into the mould. In fig. 42 is shown this method of bottom casting. The metal is teemed down a central pipe or "git," shown in section, C D, lined with fire-brick or a ramming of ganister daubed with fire-clay, and then flows through the runner-pipes to the ingot moulds, arranged on each side or radially (fig. 42); teeming is continued until the group of moulds is full. Sometimes an ingot mould is used as a "git" for casting, but if a number of ingots are being cast in a group, the large quantity of metal passing down this central mould shortens its life very considerably.

In some cases for special work large ingots are cast from the bottom in groups of 3 or 4 according to their sizes. Fig. 43 is a sketch of an ingot

mould used for bottom casting, showing details of cover for closing the top and method of wedging the cover down.

Various methods of casting small ingots in groups have been suggested from time to time, and Mr. Pink, of Hœrde, was the first to suggest that of casting ingots superimposed upon each other, and carried it out with more or less success. The tendency of late years has been to cast larger and

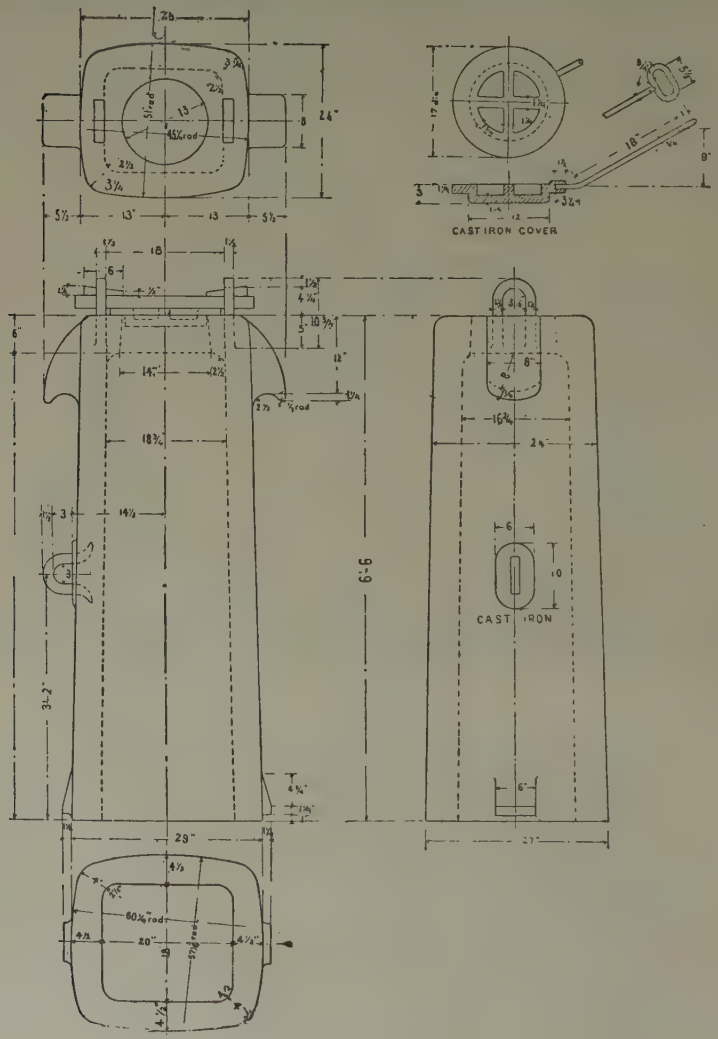


Fig. 43.—Closed Top Ingot Mould for Bottom Casting.

larger ingots, and cog down to blooms in the mill, finally rolling these to the required sections. To meet special conditions, however, small ingots are still cast, and one of the systems which has met with most practical success is that patented some years ago by Mr. Thos. Turner, of Kilmarnock. Its chief features are the grouping of a number of ingots on one bottom-

PLATE II.—The Thomas Turner Patent System of Cutting Small Ingots.

[To face page 36.

Fig. 46.

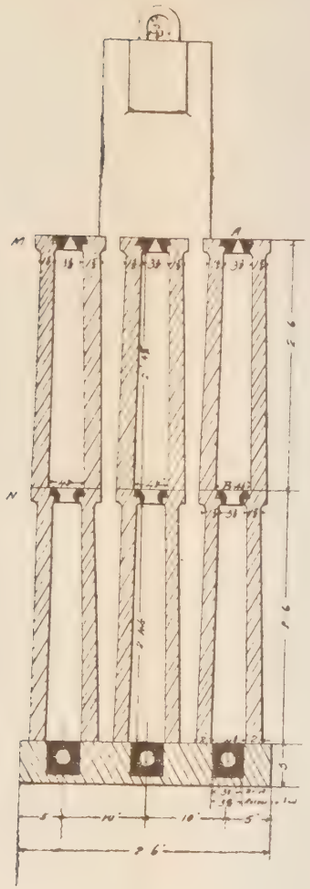


Fig. 44.

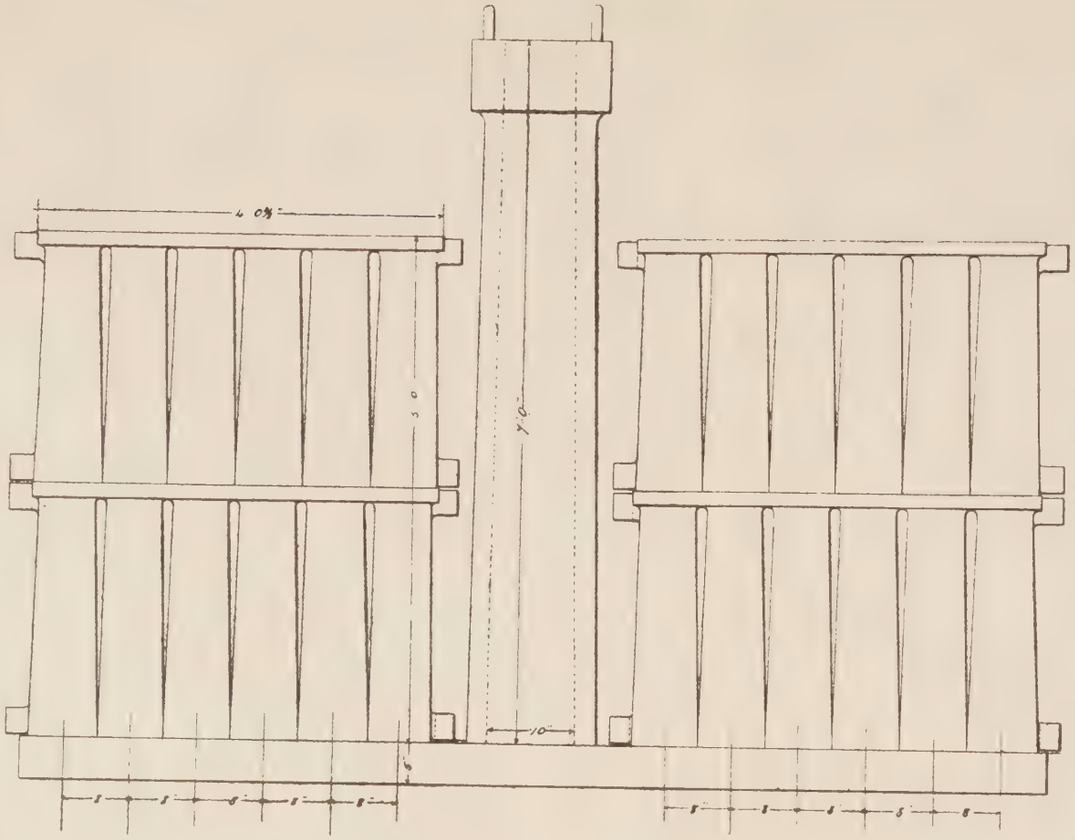


Fig. 48.

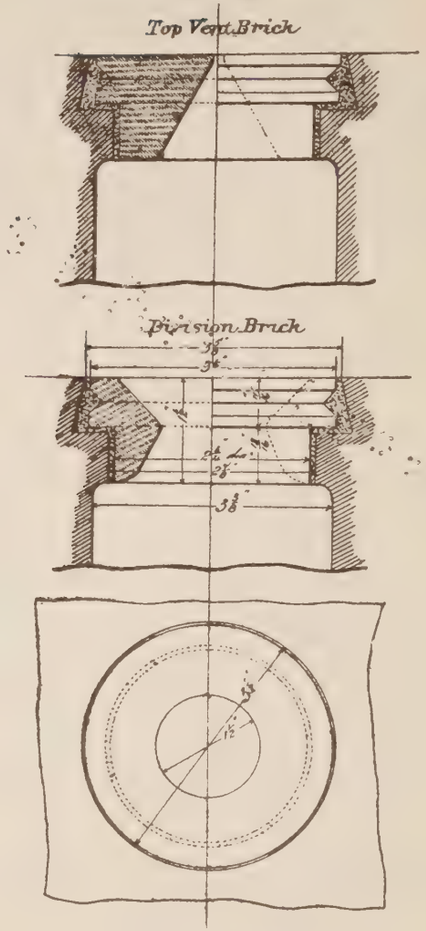
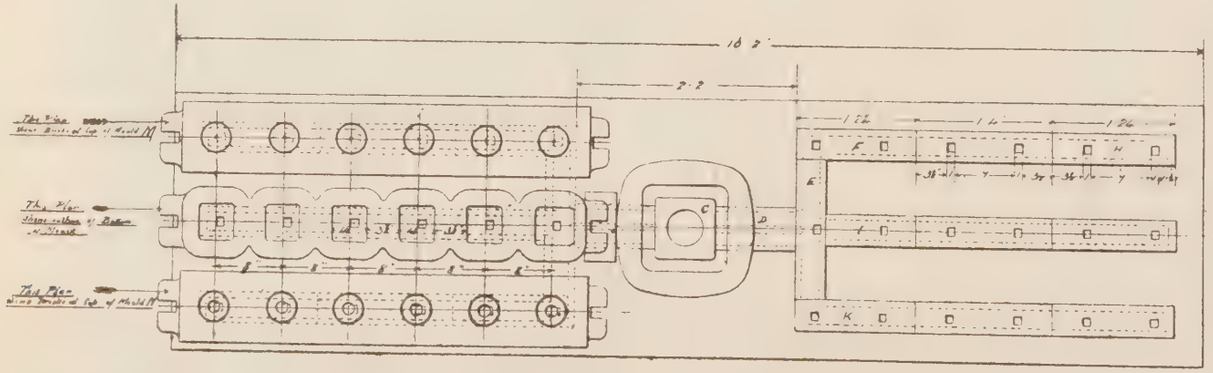


Fig. 47.



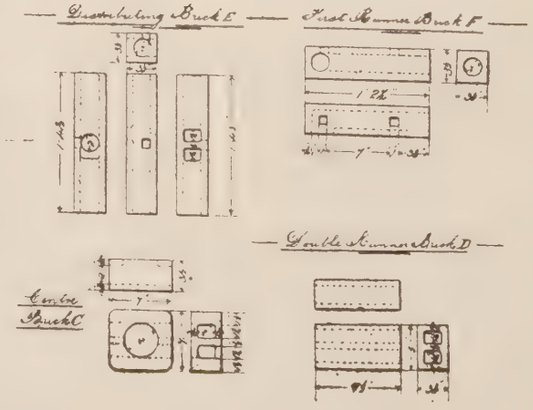


Fig. 45.

plate, and the superimposing of one set of moulds upon another. The general arrangement in plan and elevation is shown in figs. 44 and 45, in which there are only two sets of moulds, one over the other, although in some cases they are cast three high. Between each bottom and top mould is inserted a division brick, as shown in figs. 46 and 47, which allows the steel to flow from the bottom to the top mould without chilling, and the top set of moulds has a vent brick inserted in each (fig. 48.) The top ingots are thus connected by a short neck to each of the bottom ingots; these necks, however, part very readily when the moulds are stripped off and the ingots lifted up, as they are very short and contract less than the ingot, owing to their being kept hot by the bricks.

As many as 120 ingots have frequently been cast by this system from one charge of steel, and it was the regular custom for some years to cast 72 ingots from 10 tons of metal at the Weardale Steel Co. The usual size of ingots cast is from 4 to 7 inches square, or 6-inch by 5-inch slabs. Some years ago the author saw the system at work near Birmingham, and, so far as could be seen, the results were very satisfactory. Provided that special conditions render it necessary to cast small ingots, this method of casting is as good as any that has been devised. The cost of making such ingots must, however, always be heavy, owing to the labour of stripping, cost of runner bricks and production of wasters, resulting from some of the moulds not completely filling, especially if the metal is rather cold. It is therefore only applicable to small works where they have not the necessary plant to cog down large ingots, and where special considerations render it essential that they should make their own steel rather than purchase billets, &c., from large steel makers. It need hardly be pointed out that in all systems for casting small ingots in groups, it is essential that the metal should be teemed hot, otherwise very few of the moulds will fill.

Bottom Casting *versus* Top Casting.—The question of bottom *versus* top casting is one that has been much discussed, and generally it may be said that when small ingots are required, bottom casting is resorted to, but that large ingots are more usually cast from the top. The general opinion is that sounder ingots are obtained by using closed-top moulds and casting from the bottom, and when specially sound material is required for forgings, &c., even large ingots are often cast in this way. In the case of small ingots it would be impossible to cast them all separately, especially when dealing with dead soft steel, as the metal would set in the ladle round the nozzle before they could be all filled. One of the great disadvantages of bottom casting is the large amount of runner scrap made, as each runner brick is full of metal, and this has to be re-melted as scrap. Another serious matter is the extra labour in removing the ingots from the mould and breaking off the steel runners from each ingot. To overcome these difficulties, at the new steel plant of the Hamilton Steel and Iron Co. in the United States, the bottom runner is replaced by a horizontal ingot or big runner, so that all loss from runner scrap is done away with. The vertical ingot moulds are separated from the horizontal runner by bricks, 1 inch thick, which are let into the bottom casting plate, and these bricks have holes under each mould to allow the steel to come up from below.

When the vertical ingot moulds are stripped off the horizontal ingot, the short necks of steel connecting these ingots to the horizontal one are easily broken, and the moulds are at once placed on another bottom-plate resting on a car ready for another cast. The ingots are 6 inches square and $5\frac{1}{2}$ feet long, and are cast in groups of 22, three sets being required

to take the furnace charge. The horizontal ingots are said to be perfectly sound and to give excellent results in the mill. The bottom-plates carrying each group of ingots rest on cars and are run under the nozzle of the ladle, although in the particular works mentioned, a fore hearth or ladle attached to the tilting furnace is used. This will be found described under the heading of the Wellman tilting furnace.

Ingot Cranes.—In the older works the ingots are all cast in pits, known as casting pits, of such a depth that the top of the mould stands a

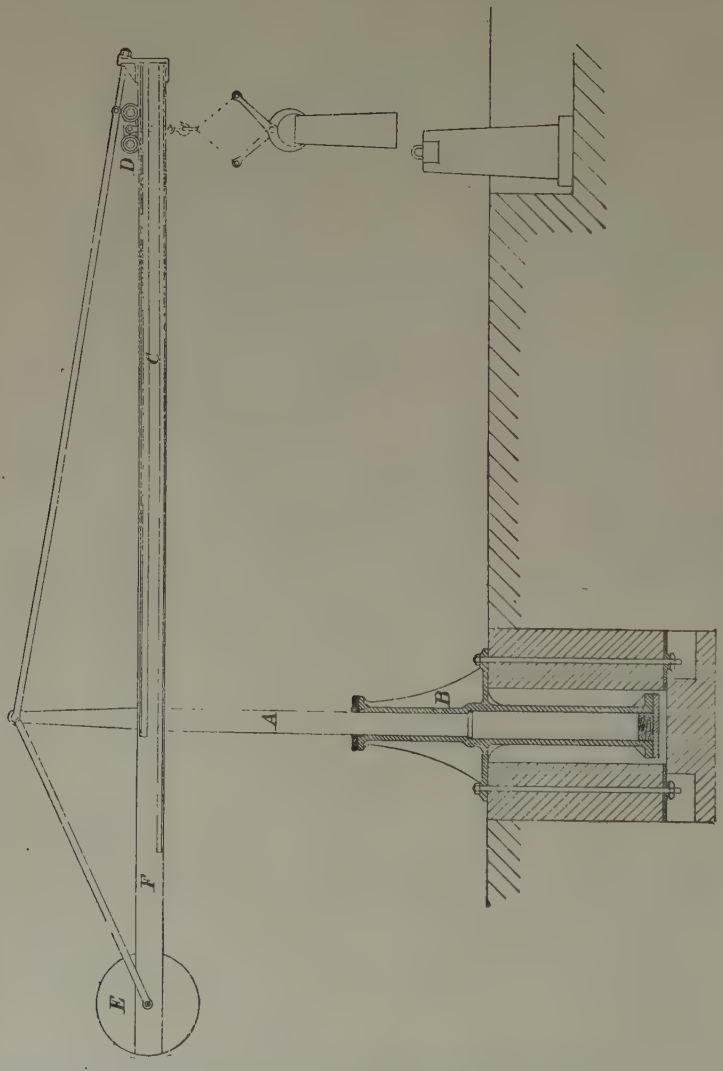


Fig. 49.—Bottom-supported Ingot Crane.

little above the ground level. After standing a few moments to enable the fluid metal to set, the hot moulds are lifted off the ingots by a crane by the wrought-iron loops which are cast into the moulds, and to which the

crane hooks are attached. Two or three cranes are usually provided for each pit, and are generally of the type known as "ingot cranes," first devised by Sir Henry Bessemer; cranes much more rapid in action than any existing when his process was introduced became a necessity, if the output, even of those days, was to be removed with sufficient rapidity to prevent the melting department standing idle while the pit was being cleared.

The ingot crane (fig. 49) consists of a ram, A, standing vertically in a cylinder, B, into which it fits freely, capable of being raised by admitting to the cylinder water under a pressure most frequently of 400 to 800 lbs. per square inch, whereby the ram is raised to the height required, and, the admission valve being closed, the incompressibility of the water keeps the ram perfectly steady. By opening a second valve the water can be run out, and the ram descends at any speed desired. From the ram projects a horizontal arm or jib, C, on which a small carriage D, provided with a hook, can travel to and fro, a weight, E, on an arm, F, projecting from the opposite

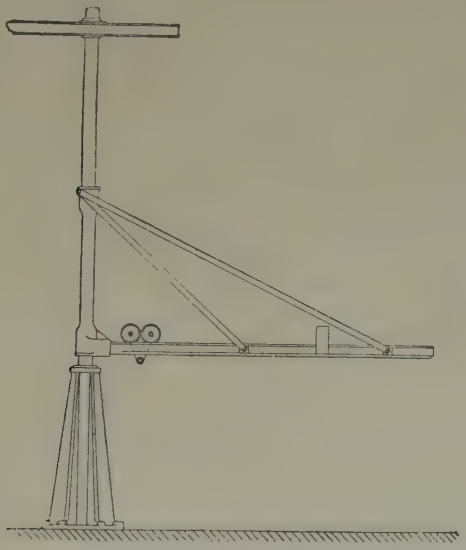


Fig. 50.—Top-supported Ingot Crane.

side of the ram, partially balances the load. The ram, being supported on the water, turns very easily, and a workman, provided with a hooked rod, can run the load backwards and forwards along the jib, or swing the whole crane round with loads of 1 or 1½ tons. For weights greater than this some method of travelling the load along the jib is usually provided; either a hand purchase or a small direct-acting cylinder. In England the only support for the ram is usually the cylinder below the jib, but in America the ram is carried up into the roof (fig. 50), where a second support is provided, the crane being then known as a top-supported crane.

Fig. 51 shows a top-supported Wellman crane, with details of foundation, &c.

The ordinary ingot crane consumes a vast quantity of water compared with the useful work done by it, which is only about one-third to one-sixth of the total energy expended, and a large number of devices have been

employed in view of overcoming this defect; but the extreme simplicity of Bessemer's original design, and its rapidity of working, have secured the adoption and retention of this type in the great majority of Bessemer steel works all over the world.

Stripping the Ingots.—When the ingot mould is raised by the crane, the weight of the ingot is frequently sufficient to cause it to drop out, and if the moulds are in good condition the latter will "strip" from the ingots easily, and leave them standing in the pit. This, however, is not always the case, especially when the moulds have become somewhat worn, and then it is often necessary to strike the mould heavily several times with a sledge, while it is suspended from the crane, before the ingot will fall out.

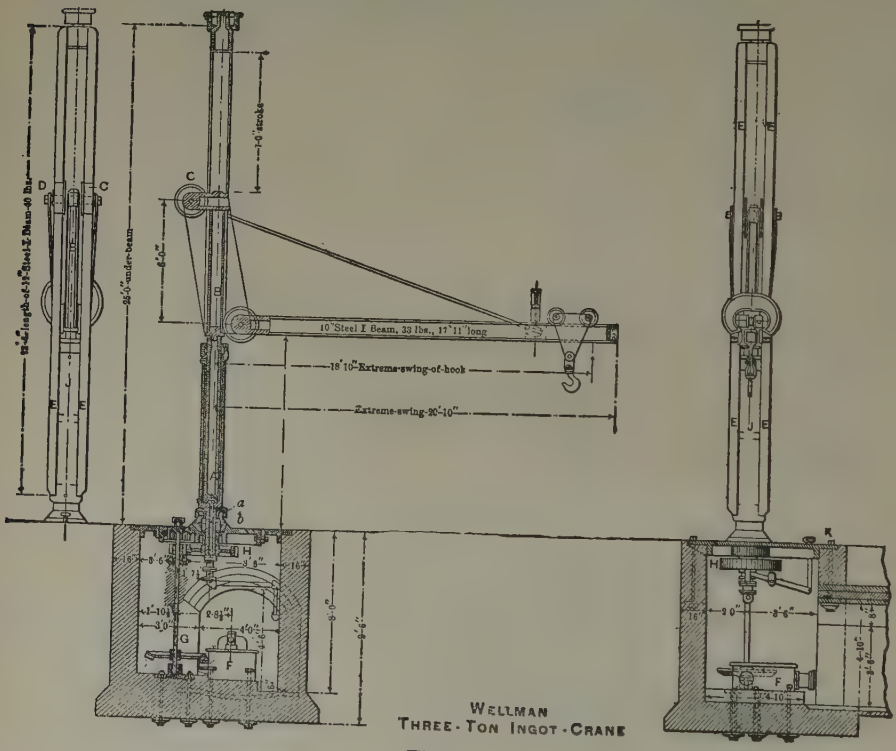


Fig. 51.

When the moulds are in bad condition the amount of sledging may be very considerable, and the cost of labour and the delay are serious matters. To obviate these difficulties in modern works where casting on cars has not been adopted, the ingot moulds, with the ingots in them, are hoisted by the ingot crane upon a bogey, and taken away to a hydraulic ram, known as a stripper, which rapidly removes the ingots from the moulds, and places the latter on another bogey to be returned to the Bessemer shop. In an old-fashioned Bessemer shop, where all the ingots are stripped at the pit,

the heat from the masses of hot metal is very trying to the men, and largely interferes with their work, and one of the advantages of the ingot stripper is that it can be any reasonable distance from the Bessemer shop, and consequently the stripping does not interfere with the work at the casting pit.

The "Ingot Stripper" is a most efficient machine, not only saving considerable amount of labour, but also all damage to the moulds from sledging to remove the ingots. The Evans ingot stripper, which has been giving most satisfactory results at the works of Messrs. Crawshay Bros., Cyfarthfa, South Wales, since 1898, is designed to strip two ingots at a time, and is illustrated in figs. 52, 53, and 54, which, together with the description, are taken from the *Iron and Coal Trades Review*. Both long and short ingots can be stripped with equal ease, the shortest piece on which the stripper will exert its full force of 75 tons being 1 foot 6 inches. The height of this stripper is 34 feet 9 inches, which is considerably less than that of many others. The reduction in height is obtained by the use of three comparatively short rams, instead of one long one (which is used in some other strippers), whereby the long stroke of this one ram is converted into two comparatively short strokes, giving the machine a great increase in stability, &c. When a stripper is used, it is necessary to have lugs cast on the outside of the mould, as shown in fig. 52, instead of loops as shown in figs. 38 to 41, in the old form of moulds intended for hand-stripping.

Of the three stripping rams shown in the figures, the two outside ones (fig. 52), pull the mould up, while the centre ram holds the ingot down. The centre ram uses no pressure water, but is kept immovable at the top of the ingot by means of non-pressure water, which flows by gravity into the barrel of the ram, and being locked therein by an automatic operating valve, prevents the ram from rising. This non-pressure water is again liberated automatically when the stripping is complete by means of the above-mentioned valve.

The consumption of pressure water is also greatly economised by differentiating the diameters of the side rams, a large diameter being used for the initial pull upon the mould, and a smaller diameter for the easier work of raising the mould clear of the ingot.

The working of the machine is made exceedingly simple for the operator, since all he has to do is to take the pressure off, thus allowing the three rams to descend, the centre ram stopping of itself upon the top of the ingot and the two side rams continuing to descend until the stirrups engage the lugs upon the mould, when he puts the pressure on, raises the mould, and so completes the operation.

The machine consists of the following parts :—

1. The gantry, A (fig 52), spanning the two roads B and C, B being the road upon which the bogies carrying the full moulds are brought up, and C being the road upon which the bogies carrying the empty moulds are returned to the casting shop.

2. The carriage, D, upon which are the two sets of stripping cylinders. This carriage is moved backward or forward along the gantry by means of the traversing cylinders, E, with their rams, F.

The drawings represent the machine as designed to strip two ingots at one time ; there are, therefore, two sets of stripping cylinders with their rams, each set capable of being worked either independently or together.

Each set of stripping cylinders comprises :—

1. Two outside differential rams, G, with their top barrels, H, and bottom barrels, I ; each of these outside rams has a hole, J, in its centre, through which the pressure is conveyed from the bottom barrel of large diameter to

the top barrel of small diameter. When the pressure is put into the bottom barrels, I, the two rams, G, together with their top barrels, are raised through the stroke allowed by the bottom barrels; the pressure water then finds its way through the holes, J, in the side rams, G, and acts upon the tops of these rams, raising the top barrels through the stroke allowed them.

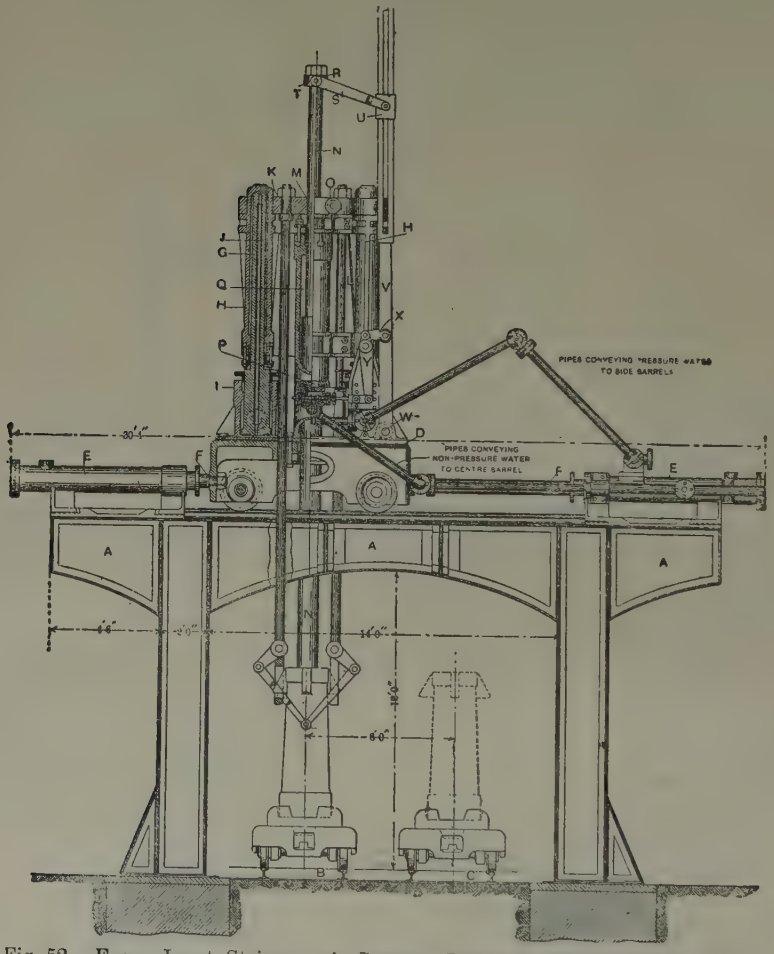


Fig. 52.—Evans Ingot Stripper—A, Gantry; B, truck with full ingot moulds; C, truck with empty moulds; D, carriage carrying stripping cylinders; E and F, hydraulic cylinders and rams for moving D; G, two outside differential rams; H and I, top and bottom barrels for rams G; J, central hole in ram G; K, crosshead; L, slings connected to K to engage lugs on ingot moulds; M, hole in crosshead for N to pass through; N, centre ram; O, friction roller; P, valve controlling supply of non-pressure water to centre barrel, Q; Q, barrel for centre ram, N; R, boss on top centre ram; S, lever; T, heel on level; U, block embracing lever V; V, a lever pivoted at W; X, pivot connecting levers V and Y.

2. A strong crosshead, K, which rests upon the tops of the upper barrels of the side rams, and to which are attached the slings, L, for engaging the lugs upon the ingot moulds. In this crosshead, midway between the two

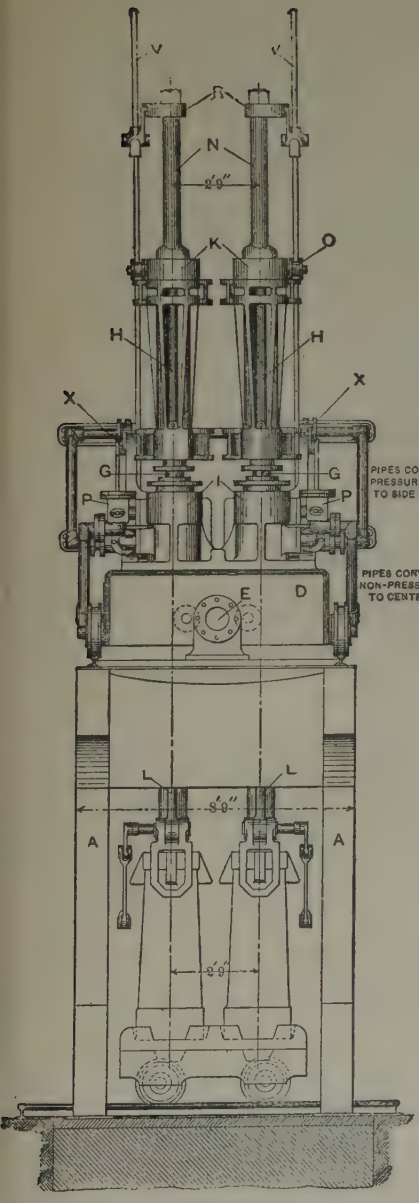


Fig. 53.—Side Elevation.

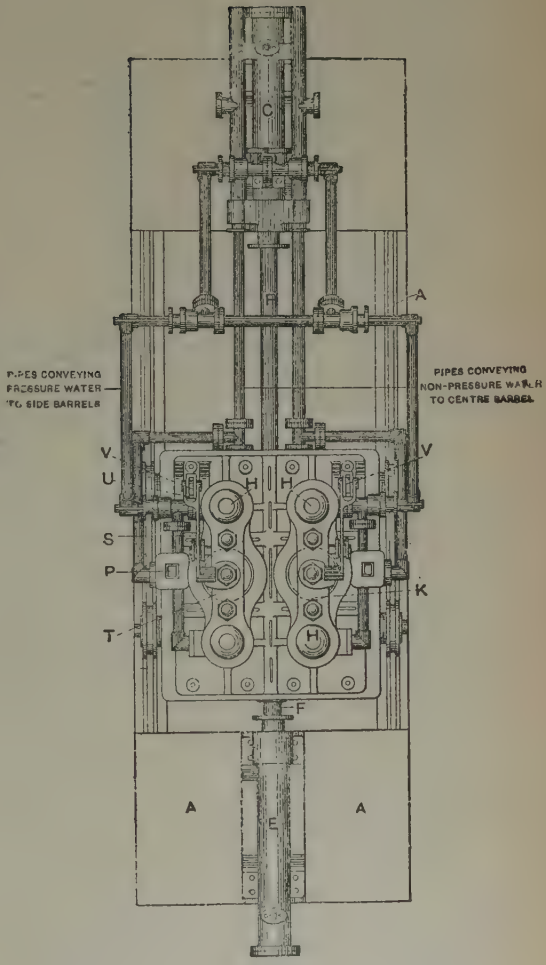


Fig. 54.—Evans Ingot Stripper—Plan.

side rams, is a hole, M, through which the extension of the centre ram, N, passes; and fixed to the side of the crosshead is a friction roller, O, which operates the automatic gear for opening and shutting the valve, P, controlling the supply of non-pressure water to the centre barrel, Q.

3. The centre ram, N, with its barrel, Q, which merely acts as a stopper, preventing the ingot from rising when the mould is being pulled up. The top end of this ram is of smaller diameter than the bottom, and is furnished with a boss, R, and it is by means of this boss that the centre ram is moved, as the boss rests upon the crosshead whenever the centre ram is not upon an ingot. To the top of the centre ram is attached the lever, S, which is operated by the friction roller, O, and which operates in its turn the levers for working the automatic valve controlling the supply of non-pressure water to the centre barrel.

4. The automatic gear for operating the valve controlling the supply of non-pressure water to the centre barrel, consisting of the lever, S, which is attached to the boss, R. This lever has a heel, T, which engages a projection upon the boss, and thus its downward movement is restricted. Upon the other end of the lever is a side block, U, embracing the long lever, V, which is pivoted at W. This side block moves up and down upon the lever, and by means of its weight moves the lever in towards the centre ram, and so locks in the non-pressure water. This lever is connected at X to another lever, Y, which is connected direct to the stock of the valve, P. The object of this lever, Y, is merely to multiply the stroke of the lever, V, so as to insure sufficient stroke for the valve, P.

Assuming that there is a bogie containing a full mould under the stripper, upon the road, B, and that the stripping rams are raised ready for lowering upon the ingot, and also that there is an empty bogie upon the road, C, for receiving the moulds when stripped off the ingots; then, the rams being in the same position, the crosshead, K, will be supporting the centre ram, N, by means of its boss, and consequently the friction roller, O, will be up against the lever, S, holding the latter in a horizontal position. When this is the case, the other levers—viz., V and Y—will occupy such positions as to keep the valve, P, open, so that there is free access for the non-pressure water into the barrel of the centre ram.

The operator now takes the pressure from beneath the two side rams, G, causing these rams, together with their top barrels, the crosshead and the centre ram, to descend together.

The whole of the above descend together until the centre ram comes in contact with the top of the ingot—which is either a short piece or full-sized—when the centre ram stops; but the two side rams, together with their top barrels and the crosshead, continue to descend, and in descending the friction roller, O, leaves the lever, S, which drops by means of the weight of the side block, U, into the position shown in the drawing. This movement of the lever, S, draws in the long lever, V, and so shuts the valve, P, so that the non-pressure water is now locked in the centre barrel. The side rams continue to descend until they reach the bottom of their lower barrels, but the top barrels still descend until the stirrups on the slings engage the lugs on the ingot moulds.

The operator now puts the pressure under the side rams, which, together with their top barrels and the crosshead, K, rise, and so strip the mould off the ingot, as the centre ram is unable to rise owing to the non-pressure water being locked in its barrel. The side rams, with their top barrels, together with the crosshead, continue to rise until the friction roller again comes in contact with the lever, S, and raising it again into a horizontal position, pushes out the long lever, V, and so unlocks the water from the

centre cylinder by opening the valve, P. The centre ram, N, is now able, by means of its boss, to be raised by the crosshead, K, and thus the crosshead and centre ram now rise together; the crosshead, by means of the slings, carrying the moulds, which have been stripped.

The pressure being still under the side rams, the operator now moves the carriage, D, above the road, C, by means of the traversing cylinders, E,

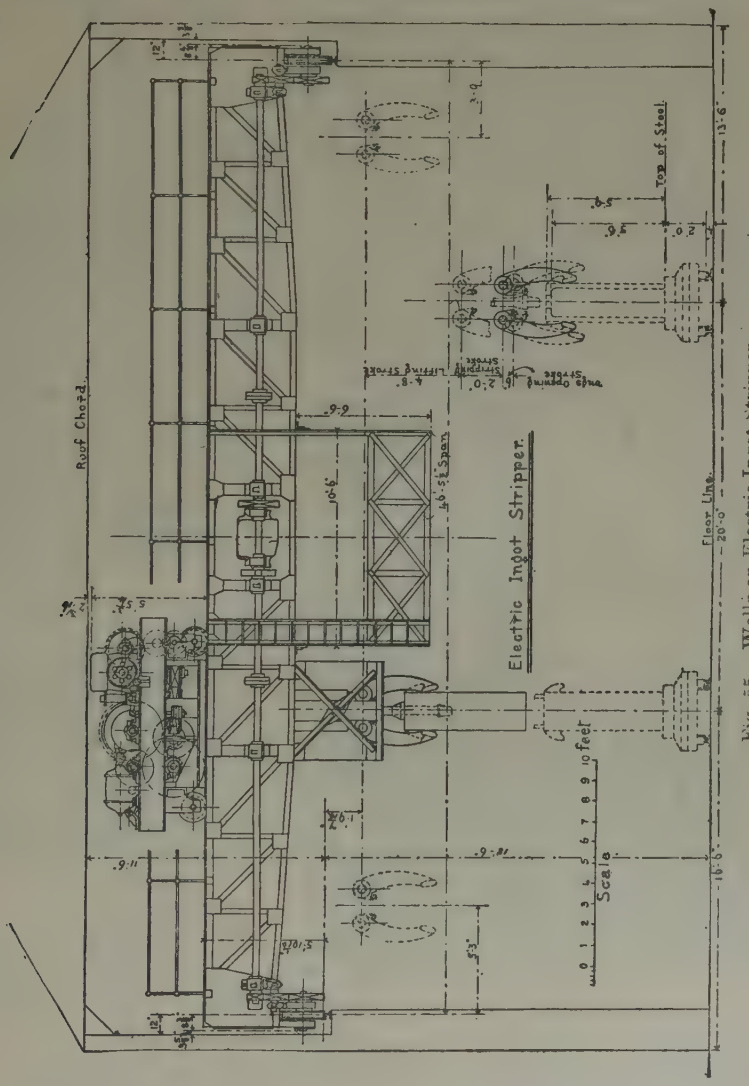


Fig. 55.—Wellman Electric Ingot Stripper.

carrying with it the stripping cylinders and also the moulds. When the empty moulds are over the bogie, which is ready to receive them, the operator takes the pressure from under the side rams, allowing the moulds to be lowered on to the above-mentioned bogie; the stirrups on the slings automatically disengaging themselves from the lugs on the ingot moulds by

means of a simple arrangement of a chain and weights not shown on the drawings. The operator now moves the carriage, D, carrying the stripping cylinders, back above the road, B, in readiness for the next ingots brought up, thus completing the operation.

One of the early forms of electric strippers designed by the Wellman-Seaver Engineering Company is shown in fig. 55. It consists of an ordinary electric travelling crane with the operating cage suspended from the middle of one of the main girders, and special appliances for seizing the ingot mould and removing it from the ingot. The electric traveller is fitted with three motors—one (25 H.P.) fixed outside

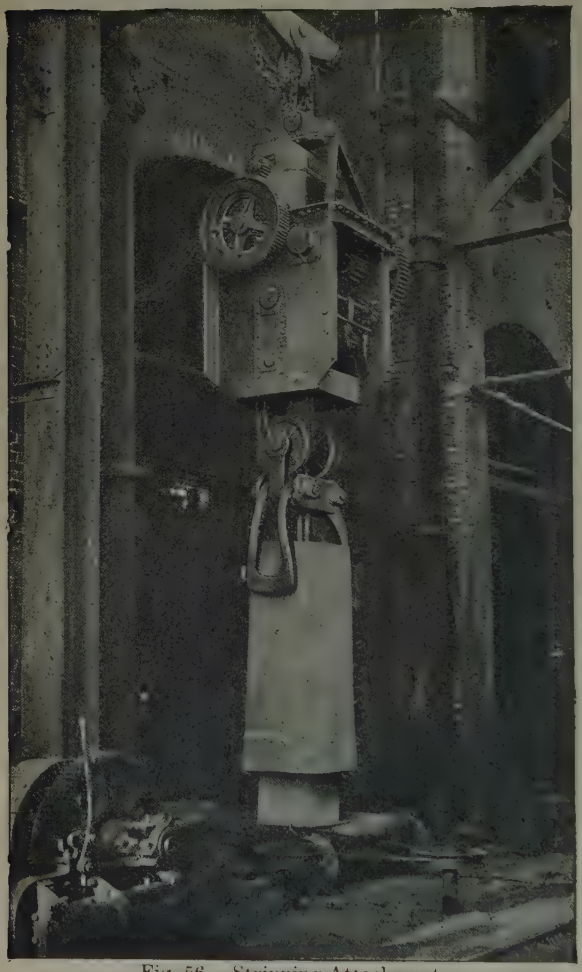


Fig. 56.—Stripping Attachment.

These attachments are electrically operated, either by a switch from the ground or from the operator's cabin of any existing crane, from which it may be suspended. A stripping pressure of 150 tons, sufficient to remove the worst stickers, can be exerted.

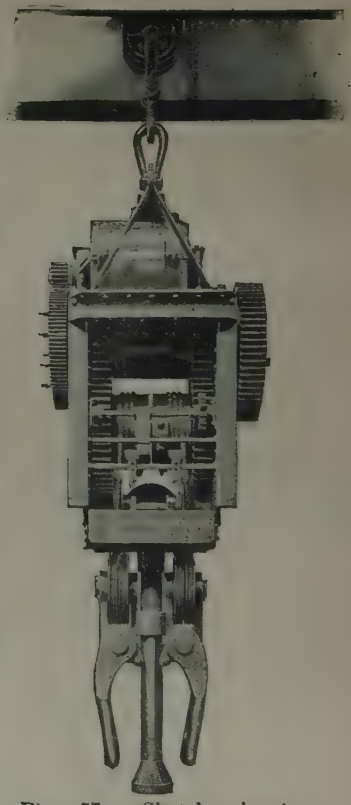


Fig. 57. — Sketch showing Details of Ingot Stripper Attachment.

one of the two main girders which carry the trolley for effecting the longitudinal traverse of the whole machine; one (5 H.P.) for cross traverse of the trolley, and another (25 H.P.) for driving the hoisting and lowering gear, the

last two being of course on the trolley. Two more motors, also on the trolley, furnish the power required to operate the extractor. One (3½ H.P.) is used to rotate the vertical sleeve carrying the extractors about its axis, thus enabling the machine to pick up an ingot mould which has not been placed square underneath it; the other (100 H.P.) furnishes the power necessary for the separation of the mould from the ingot In this last operation the electric stripper possesses an economic advantage over the hydraulic stripper, because in the former case the energy expended is proportional in each case to the resistance to be overcome in starting the mould from the ingot, whereas in the hydraulic machine an equal quantity of water at a constant pressure

Fig. 58.—Guided Ingot Stripper.

The stripping gear is similar to the stripping attachment (fig. 57), but guided. The gear is carried on a trolley on the main girders, which traverses across similar to an ordinary overhead crane. All the motions—stripping, hoisting, cross traverse, and long travelling—are under the complete control of one man.

is consumed, whether dealing with a "sticker" or with an ingot that drops out of its mould without the application of any appreciable force. The hoisting motor is fitted with a powerful automatic electric brake, which stops the gear dead in any position when for any reason the current is cut off. All other motors which are liable to over-run, or which are not stable in any position, are fitted with electrical or mechanical friction brakes.

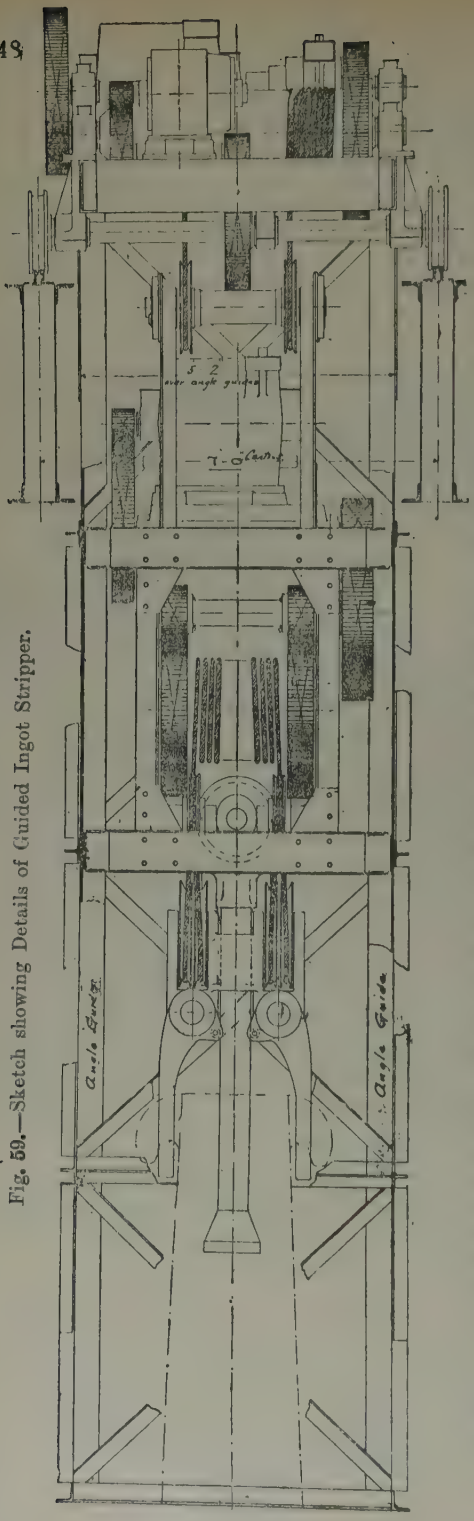


Fig. 59.—Sketch showing Details of Guided Ingot Stripper.

For works where the output is small and a separate stripper and ingot charging crane cannot be kept fully employed, a combined stripper and charger, for use with vertical ingot reheating furnaces has been designed, with what is known as a stripping attachment. This latter is installed at the works of the Soc. Siderurgica, Savona, Italy, and is illustrated in figs. 56 and 57; it can be suspended from any convenient position.

The latest form of Wellman-Seaver electric stripper is what is known as the guided ingot stripper, shown in figs. 58 and 59.

Stripping the Pit.—Whether a stripper is used or the ingots are stripped at the pit, a most important point is their rapid removal from the pit, and the substitution of empty moulds ready for the next charge. It is also essential to have ample facilities for repairing and re-stoppering, and when necessary the replacement of ladles by re-lined ladles. These operations can keep pace with rapid blowing only if ample crane power is provided; and ingot cranes should be arranged round the pit as close together as possible, just sufficient room being allowed for their respective jibs to swing clear of each other.

Generally one end of the pit, or in the case of a very large pit where two or three centre cranes serve four or more converters, each end of the pit is reserved for minor ladle repairs, such as removing slag, patching ladles, replacing nozzles, &c. Such an arrangement of cranes is shown in the plan of the North-Eastern Steel Co. (fig. 63), which may be taken as typical of the practice prevailing at works where pit casting is still maintained.

The actual re-lining is more

generally done in a separate shed, generally a part of, or near to, the converter bottom repairing shop, where a furnace is usually provided for drying ladles.

Arrangement of Bessemer Shop.—Having described the principal appliances used in Bessemer works, there now remains to be considered the

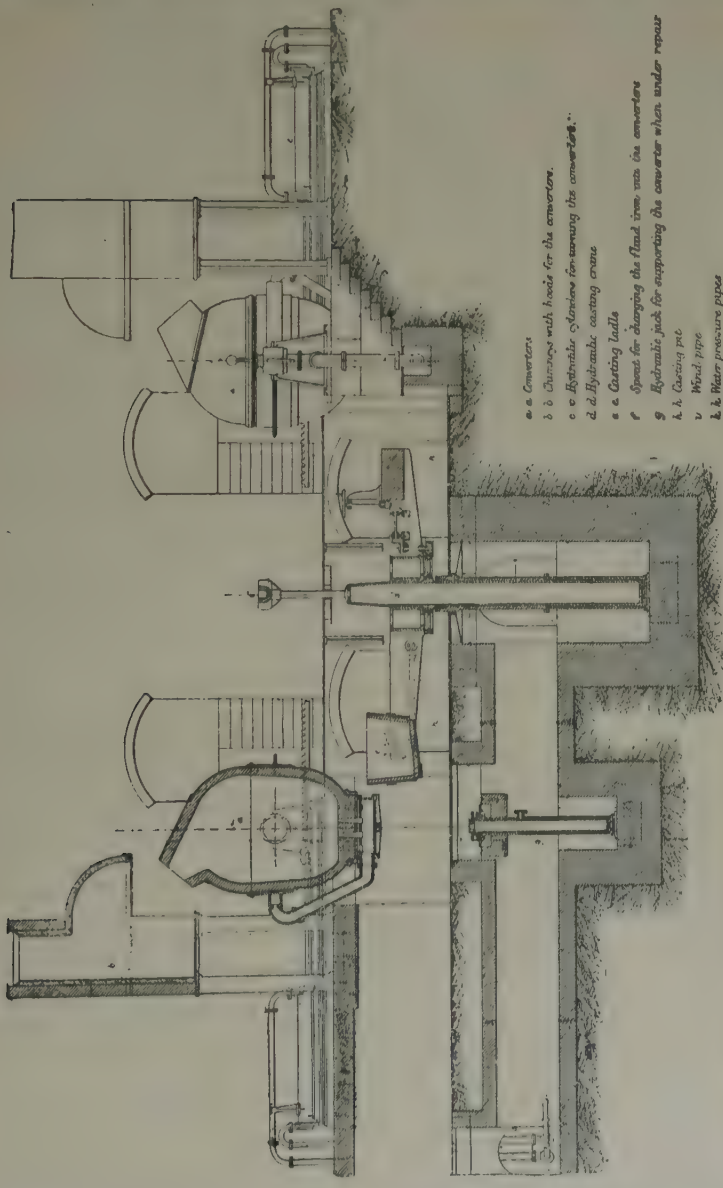

a a. Converters
b b. Chimneys with hoods for the converters.
c c. Hydraulic cylinders for turning the converters.
d d. Hydraulic casting cranes
e e. Casting ladle
f. Spout for charging the fluid iron into the converters
g. Hydraulic jack for supporting the converter when under repair
i. i. Casting pit
l. Wind pipe
k. k. Water pressure pipes

Fig. 60.—Bessemer Plant showing arrangement of Converters, Casting Ladle, and deep Casting Pit in early English Plants.

disposition of plant best suited for carrying out the various operations during the process of manufacture.

It is necessary that the operations should be conducted so that they in

no way interfere with each other, with the minimum expenditure of labour and time, and with as little wear and tear to the machinery as possible.

In the early Bessemer plants it was usual to place one converter on each side of a deep circular pit, so that they could each be served by one centre crane carrying the ladle, the casting pit being between the two vessels, as shown in fig. 60. Cupola metal was always used, the cupolas both for melting the iron and spiegel being arranged on a platform at such a level that when the converter was turned down the molten pig-iron could be tapped either directly into the vessel by means of a runner, or into a ladle at the same level as the converter, so that after weighing the metal could be poured into the latter. Although many works designed in this way have done excellent work, still, in these days of large outputs, the working space is so cramped that it is impossible to handle the moulds, ingots, ladles, &c., rapidly enough, and the heat on the cupola platform and in the pit becomes so excessive, that it is impossible for the men to do as much work in a given time as they would do under better conditions.

To avoid these disadvantages, the first step was to increase the working space in front of the converters, and instead of placing the latter opposite each other, the converters were placed in one line, and the deep circular pit was replaced by a large shallow semi-circular or circular one.

Two converters are usually served by one central casting crane similar to that described in fig. 36, the radius of the jib being such that it carries the casting ladle well under the converter at the back of the pit, and allows it, when swung round, to cover the ingot moulds, which are generally arranged round the circumference of the pit.

If the metal is poured direct into the ladle on the centre crane, the distance between the converters and the circumference of the pit is limited by the radius of the jib of the crane, and as a modern crane constructed as shown (fig. 36) will have to carry from 12 to 15 tons of metal in the ladle, the maximum length of jib consistent with safety and easy handling is soon reached. Various devices have been suggested to meet this difficulty, and one in use in this country is to have special jib cranes arranged near the converters, known as the receiving cranes, on which the metal ladle is supported during the pouring of the metal from the converter.

The ladle is then transferred to the centre casting crane by bringing the jibs of the two cranes together, and lifting the ladle bodily from the receiving crane. This plan is in use in the North-Eastern Steel Works, Middlesbrough, and it increases the working space between the circumference of the pit and the converter by an additional distance equal to the length of the jib of the receiving crane. Figs. 61 and 62 are fairly representative of many existing English and American Bessemer plants, although, as will be shown, in the most modern works the pit is being dispensed with altogether. The description accompanying the drawings explains the details. In America, at South Chicago Union and Wheeling,* this removal of vessels from the casting pit is carried a step further. The metal is poured into the ladle on a receiving crane with a short jib near the converter, from which it is transferred to a track leading to the casting pit, along which it is pushed by a hydraulic ram attached to the receiving crane, and it is then drawn on to the casting centre crane by the radial hydraulic cylinder of the latter. This increases the distance between the converters and the circumference of the pit by the length of the track.

In some Continental works the circular pit is dispensed with, and a straight pit used, in which case it can be either in a line with, or parallel to, the converters; the metal is then poured into a ladle, supported on a carriage

* Howe, *Metallurgy of Steel*, pp. 331 and 332.

PLATE III.—Bessemer Steel Plant—General Arrangement.

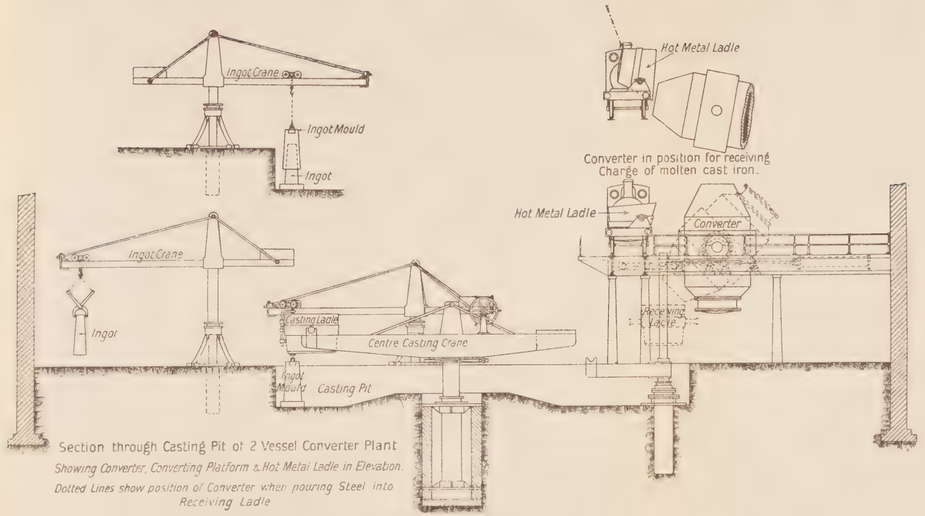
[*To face page 50.*

The sketch shows the general arrangement of Bessemer Plant, with receiving crane, casting crane, and ingot cranes. The hot metal is brought in the ladle along an elevated railway track in front of the converters, as shown in plan and elevation. Molten iron is poured from the ladle into the converter by attaching one end of a chain to a lug on its bottom, and tilting, as shown in the sketch, by means of a hydraulic ram or other suitable appliance connected with the other end of the chain.

In the elevation the converter is shown in the three different positions—nearly horizontal with molten cast iron being poured in through the nose from the ladle, vertical for blowing, and in the position for teeming into the receiving ladle, the latter being shown by dotted lines.

The receiving crane, as shown in the plan, is placed between the two converters, so that the ladle which it carries can be swung under either converter as required.

The centre or casting crane is shown with casting ladle in position ready for teeming the steel into the ingot moulds. One ingot crane in the elevation is removing the mould from the ingot which remains standing in the pit, and another one is lifting an ingot after removal of the mould.

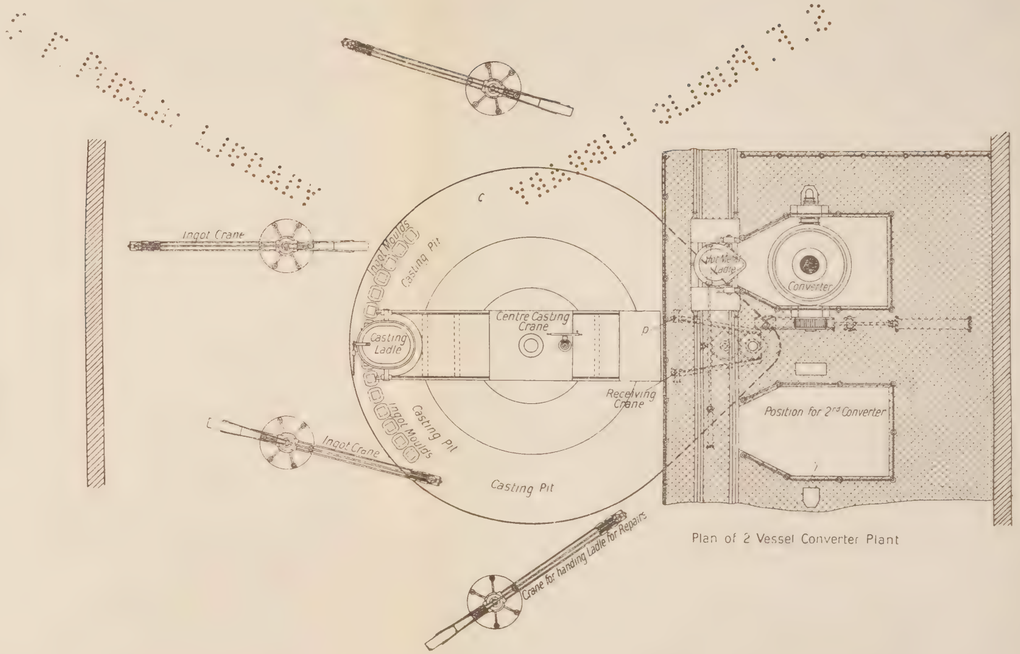


Section through Casting Pit of 2 Vessel Converter Plant

Showing Converter, Converting Platform & Hot Metal Ladle in Elevation.

Dotted Lines show position of Converter when pouring Steel into Receiving Ladle

Fig. 61.



Plan of 2 Vessel Converter Plant

Fig 62.

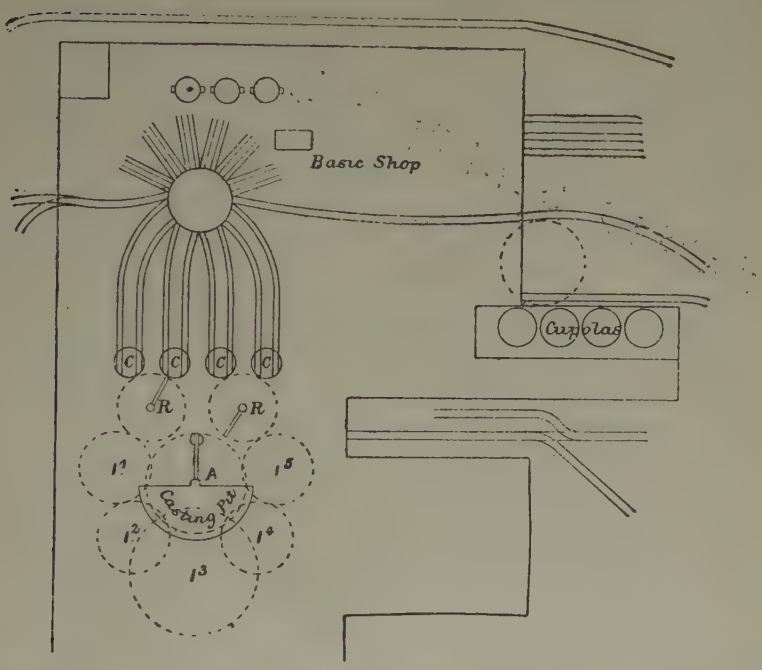


Fig. 63.—Plan of Basic Bessemer Plant, North-Eastern Steel Works.—C, Converters; R, receiving cranes; A, transfer central casting crane; I^2, I^3, I^4, ingot crane; I^1, I^5, ladle cranes.

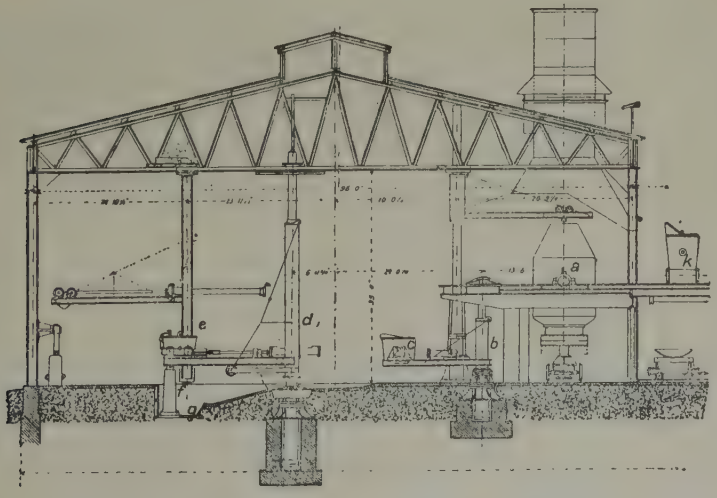


Fig. 64.—Section through the Bessemer Shop Cambria Iron Works, 1890, showing Converter with Receiving Crane and Transfer Central Casting Crane—(*a*) Converter; (*b*) receiving crane; (*c*) receiving ladle; (*d*) transfer casting crane; (*e*) casting ladle.

or on a receiving crane; in the latter case it is transferred to a carriage, and drawn along by a locomotive; but this cannot be so readily moved backwards and forwards in casting as the jib of a centre casting crane, and has no vertical movement to allow for difference in height of the ingot moulds. It has not been adopted to any extent in Bessemer works in England, although similar arrangements are in common use in Siemens works.

Fig. 63 is the plan of the Bessemer shop of the North-Eastern Steel Works, showing the central casting and receiving cranes, and fig. 64 is a section through the Bessemer shop at the Cambria Iron Works, where a similar arrangement was installed some years ago. It will be noted that the pit, even at its deepest part, is only about 3 feet 6 inches in depth, and the facility with which the ingots can be stripped and removed is very great when a comparison is made with the old circular pit shown in fig. 60.

Re-pouring Metal before Casting.—Instead of pouring the finished steel direct into the *casting ladle* on the receiving crane, in some cases the metal is poured into a *receiving ladle—i.e.*, a ladle similar to the direct metal ladle, with lip for pouring—and the metal is conveyed to the casting pit, and is re-poured into the casting ladle on the casting crane.

If the ladle is on a carriage, this allows the casting pit to be any reasonable distance from the Bessemer shop, and it also insures the thorough mixing of the steel during the transference from one ladle to another. Against these advantages must be set, especially in the case of dead soft steel, the risk of the metal being chilled and partially setting in the ladle; and as there seems little evidence that the metal is appreciably improved by re-pouring, this method of transference has not been generally adopted, the opinion of practical men, as shown by the design of recent works, being in favour of removing ladle and metal bodily to the casting crane.

Allen's Agitator.—Many years ago Mr. Allen, of Sheffield, introduced an agitator for thoroughly mixing the metal in the ladle; but although it is stated to have very appreciably improved the regularity of the steel, it has not come into general use.

Car Casting.—The most recent development in casting has resulted in the abolition of the casting pit altogether, and in the casting of the molten metal into ingot moulds, carried on bogies, running on rails at the ordinary floor level. The centre crane carrying the casting ladle full of metal is swung round into a fixed position over the first ingot mould to be filled, and instead of the ladle being moved over the next mould, each mould as it is filled is pushed forward by a mechanical appliance known as the car-pusher, and an empty one takes its place under the nozzle of the ladle. As the level of the ladle would be too high to manipulate conveniently the lever from the floor level, a tapping staging is built a few feet in height from which the teeming is done. It is very important that each mould should be placed centrally to the nozzle of the ladle to prevent the metal splashing on its sides, and also loss of metal. To insure this, the moulds are moved forward one by one by a fixed finger which is attached to a hydraulic ram on the floor level and which gears into the bogies carrying the moulds. This car pusher for moving the moulds into position is shown in figs. 65 and 66. At the Barrow Works, where this system is in operation, about 100 bogies carrying moulds are always in use, and by keeping them in proper rotation, the moulds become sufficiently cool for use again without water-cooling. About ten minutes after casting, in the case of 2-ton ingots, the bogies are drawn away to the ingot stripper, which is situated outside the Bessemer shop proper, and which strips the moulds from the ingots and places them on another bogie to be returned to the Bessemer shop for the next cast. The ingots, which are not removed from the bogie,

are then taken straight away by locomotives to the re-heating furnaces. Figs. 67 and 68 are a plan and transverse section through the Barrow Bessemer shop, kindly supplied by Mr. J. M. While, the general manager of the Barrow Company. They show a plant which is replete with every modern appliance for giving the maximum output with the minimum amount of labour. It is thoroughly typical of a first-rate modern plant.

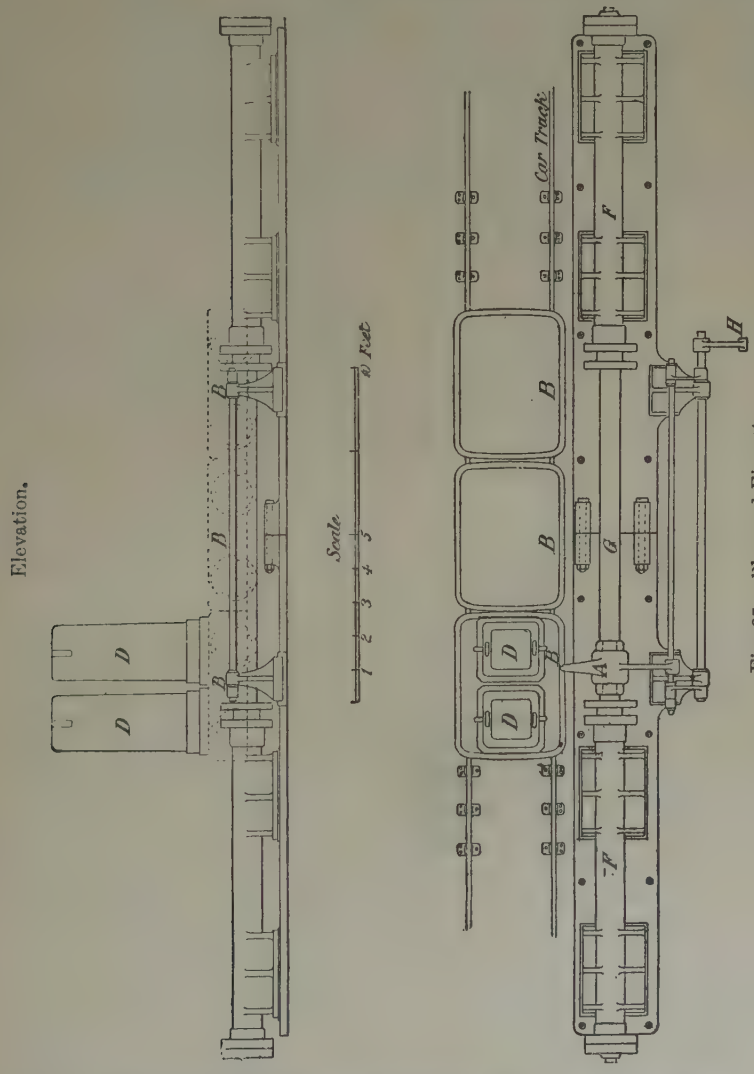


Fig. 65.—Plan and Elevation.

Car Pusher.—B, Ingot cars; D, ingot moulds; F, hydraulic cylinders; R, R, track for ingot car. By means of levers, E, E (fig. 66), the finger, A, on ram. G, may be interlocked with ingot cars. B, at will, and the cars are then pushed along until the centre of the next mould is under the nozzle of the ladle, when A is released.

The immense advantage of removing the hot ingots directly they are set, and stripping them in a shed quite separate from the Bessemer shop will be apparent to anyone who visits a modern works where car casting is employed. Not only does it greatly increase the working space and facilitate mechanical operations of the Bessemer shop in every way, but the

better conditions under which the men work enable them to do more work in a given time with less fatigue. The slow cooling of the moulds, so that all water-cooling becomes unnecessary, is also an important consideration, as their life is very appreciably prolonged.

Detailed Description of Process.

The molten metal, having been tapped either from the cupola or direct from the blast furnace, or poured from the mixer into the metal ladle, is weighed, and then raised by means of a hoist, inclined railway, or other contrivance to the converter level, and brought in front of the nose of the converter. The converter is turned down into the horizontal position, the metal poured from the ladle into it, and the latter withdrawn and returned to the cupola or mixer for another charge of molten metal. The position of the converter must be such that when the whole charge has been poured in, the twyers are well above the bath of metal, otherwise the molten iron will run into the twyer-holes.

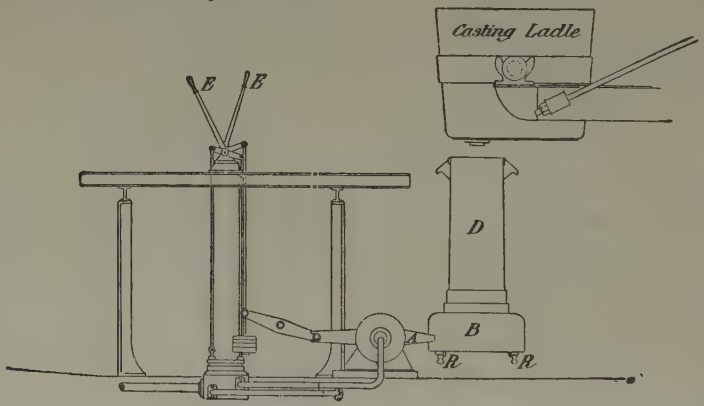


Fig. 66. –Car Pusher—End Elevation.

The blast is now turned on, and the converter turned up to the vertical position, the pressure of the blast being sufficient to keep the metal from running into the twyer-holes, and also to force its way through the molten metal. During the early stages of the blow a short flame, accompanied with showers of sparks, issues from the mouth of the converter, and gradually increases in size as the temperature of the bath is raised owing to the oxidation of the Silicon. The flame further increases in size and brightness, and evidence of very violent reaction inside the converter is given by large splashes of molten slag and some metal being ejected from the vessel. This is known as the "boil," and is due largely to the evolution of Carbonic Oxide from the oxidation of the Carbon.

"Scrapping" the Charge.—It is during this period that the "blower" decides by the appearance of the flame, &c., whether the charge requires "scrapping," and, if so, to what extent. If blowing "hot," scrap is either shot into the converter from an overhead shoot while the blow is going on, or in works where they have no arrangement of this kind, the vessel is "turned down," and scrap thrown in from the converter platform. It is very important that the metal should be regular in composition, and the Silicon should not exceed 2·5 per cent., or, for ordinary English practice, be less than 2·0 per cent. Metal much higher in Silicon is often used, but

A B, Receiving or transfer crane.
C, Casting crane.
D, Casting ladle.
E E, Ram and rack for turning centre crane.
F, Hydraulic teeming cylinder.
H, Support to casting crane during teeming.

The metal from the mixer or cupolas is brought up the inclined railway to the elevated track in front of the converters, and the metal poured by the hydraulic teeming cylinder, F (fig. 68). When the blow is finished, the steel is poured into ladle on the transfer crane, A B, the ladle transferred to centre casting crane, C, and teemed into the 2-ton ingot moulds on cars. After about ten minutes the ingots are sufficiently set to be taken to stripper, and thence to gas-heated soaking pits. About 100 moulds are kept in work, so that ample time is allowed for cooling without the use of water. At the back of converters is an inclined railway, with elevated track parallel to that in front, for the supply of refractories and scrap.

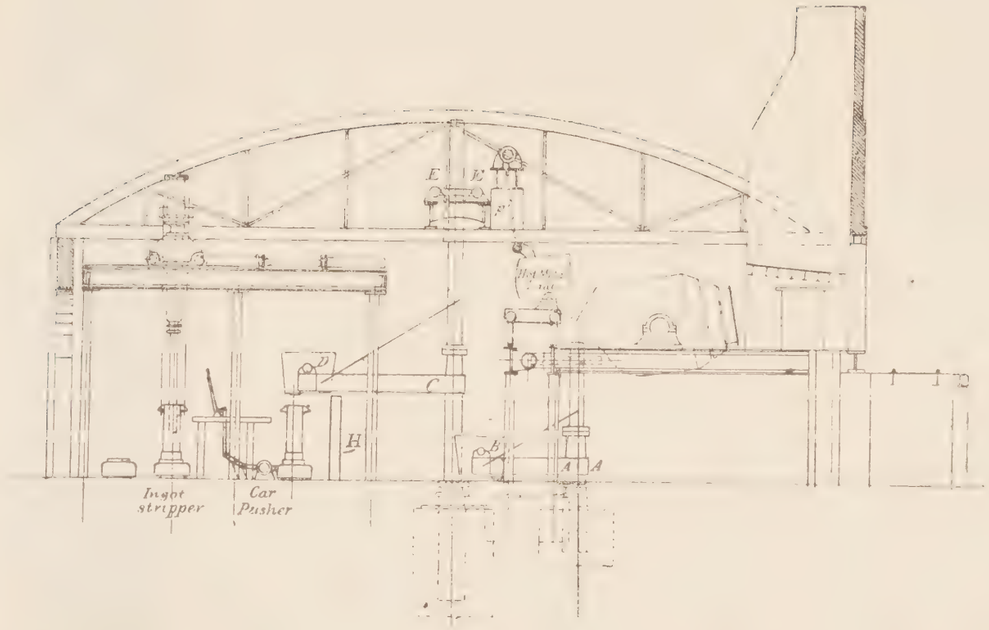
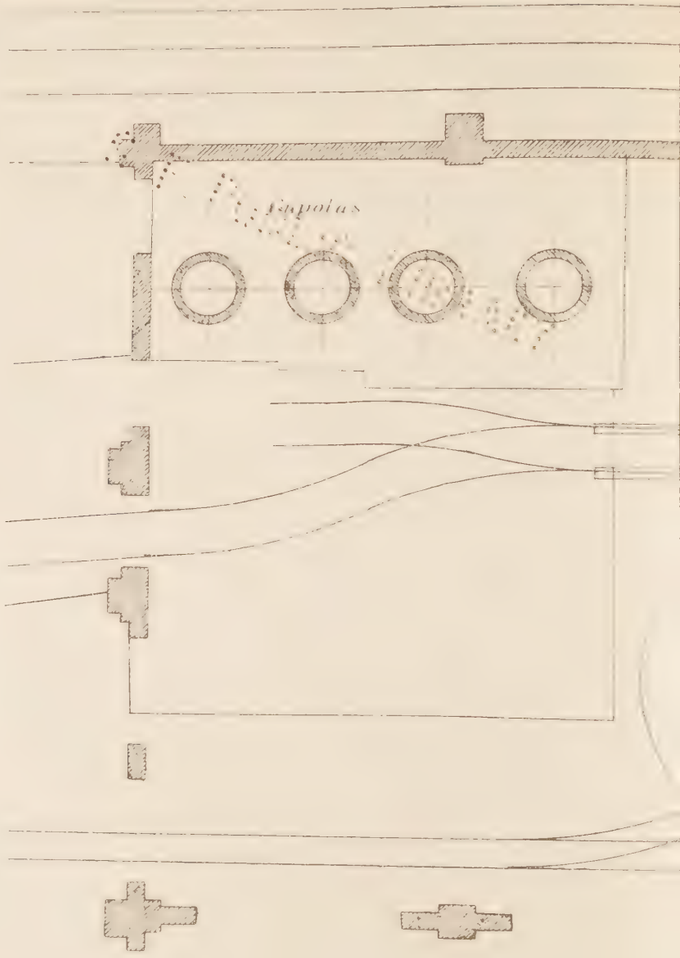


Fig. 68.



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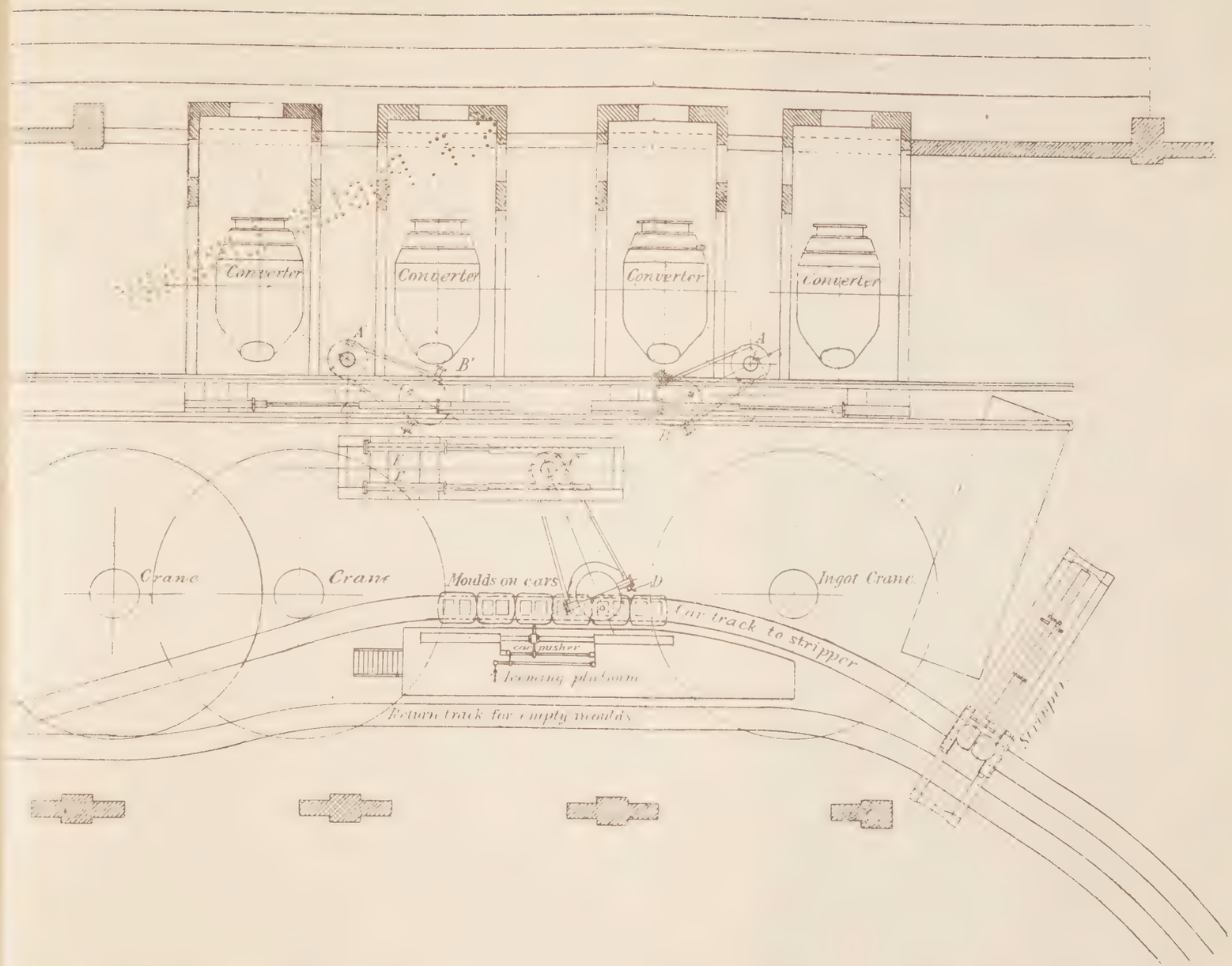

Fig. 67.

A B, Receiving or transfer crane.
C, Casting crane.
D, Casting ladle.
E E, Ram and rack for turning centre crane.
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The metal from the mixer or cupolas is brought up the inclined railway to the elevated track in front of the converters, and the metal poured by the hydraulic teeming cylinder, F (fig. 68). When the blow is finished, the steel is poured into ladle on the transfer crane, A B, the ladle transferred to centre casting crane, C, and teemed into the 2-ton ingot moulds on cars. After about ten minutes the ingots are sufficiently set to be taken to stripper, and thence to gas-heated soaking pits. About 100 moulds are kept in work, so that ample time is allowed for cooling without the use of water. At the back of converters is an inclined railway, with elevated track parallel to that in front, for the supply of refractories and scrap.

unless this is "scrapped" with great judgment "wild" metal, which produces unsound ingots, is likely to result. Gradually the action becomes less violent, the flame contracts and disappears almost entirely, this point being known as the "drop of the flame," and marking the almost complete removal of the Carbon. The converter is turned down immediately the flame drops, any further blowing tending to the production of over-blown metal, which is very liable to be red short.

Finishing the Charge.—The bath is now ready for the "additions" or "finishing metal," and the required amount of Ferro, in the case of mild or dead soft steel, and Spiegel, or Spiegel and Ferro and Hematite iron, in the case of rail or harder steels, is at once added, to give the content of Carbon and Manganese required in the finished product.

The addition of Manganese in some form to the blown metal is absolutely necessary in ordinary cases, as without it the steel is quite unworkable. When mild or dead soft steel is being made, Ferro-Manganese containing from 70 to 80 per cent. of Manganese is usually employed; this is either thrown into the converter cold, or, in some cases, first heated to redness. When higher Carbon steel is required, Spiegeleisen, which is a much poorer alloy of Manganese and iron, containing from 10 per cent. to 30 per cent. of the former, is used, and this is always melted in a cupola and added in a molten state, as the quantity required to give the right percentage of Manganese in the finished steel would often be more than the bath of molten metal would be able to melt, especially in the case of cold heats. Although Ferro-Manganese and Spiegel contain very different percentages of Manganese, the percentage of Carbon in each may be regarded for practical purposes as nearly the same, and consequently the addition of 100 lbs. Ferro containing 80 per cent. of Manganese, and 400 lbs. of Spiegel containing 20 per cent. of Manganese, although giving the same amount of Manganese, would give very different amounts of Carbon, the latter four times the quantity of the former; thus, when it is required to raise the Carbon without appreciably increasing the Manganese content, it can be done by using a large quantity of poor Spiegel low in Manganese instead of a rich Ferro-Manganese. The following may be taken as typical analyses of different percentages of Ferro-Manganeses and Spiegels, and it will be seen that the Carbon slightly decreases with the percentage of Manganese:—

	Ferro-Manganese.		Spiegels.		
	(1)	(2)	(1)	(2)	(3)
Carbon,	6·58	6·20	5·66	5·00	4·84
Silicon,	1·00	1·14	1·20	1·10	1·21
Sulphur,	Trace	Trace	Trace	Trace	Trace
Phosphorus,	0·12	0·09	0·07	0·06	0·06
Manganese,	82·00	70·00	40·50	20·40	10·21
Arsenic,	0·10	0·10	0·10	0·10	0·11
Iron,	9·90	22·20	52·30	73·20	83·40

The Phosphorus should not exceed 0·10 per cent., and if possible not 0·06, but in these days it is often very difficult to get Ferro-Manganese and Spiegel which are so low, and this is one of the difficulties with which steel makers have to contend in the manufacture of steel very low in Phosphorus.

After the addition of Ferro-Manganese or Spiegel, the metal is allowed

to remain at rest in the converter for a few minutes to allow the "additions" to melt and mix, and is then poured into the casting ladle. Some blowers turn the vessel just up and down, allowing the blast to pass through for a few seconds before pouring, to mix the charge completely. There is of course a limit to the re-carburisation to be effected by Manganese additions, and molten Hematite pig-iron is sometimes added to increase the Carbon, but this too can be used only to a limited extent for the manufacture of high Carbon steels. Darby's re-carburising process, which is described in detail in connection with basic practice, may be used with excellent results, or the blow may be stopped before all the Carbon has been removed. In Sweden it has been the practice since the early Bessemer days to stop the blow when the required Carbon point has been reached, and in some of these works no Manganese additions are made. This stopping of the blow at any required point is possible only when very small charges are blown, and when pig-iron of great regularity is employed. The pig-iron used in such cases is usually very low in Silicon and Sulphur, and high in Manganese, the latter being absolutely essential if Manganese additions are not made.

Casting.—After pouring the finished steel into the casting ladle, the latter is transferred to the centre casting crane, and the ingots cast as quickly as possible, all delays being avoided. A good blower, who generally teems the heat himself, will always see that his pitmen have a set of sharp-pointed bars at hand in case of difficulties. Teeming, which looks a very simple operation, is really one requiring very considerable skill and judgment, if sound ingots and little scrap are to be made.

Ingot moulds must not be filled too rapidly, or they will rise and "pipe"; and, on the other hand, if teeming is done too slowly, there is a very fair chance of never filling them at all, as the metal will probably set round the nozzle of the casting ladle. Sometimes a small piece of metal setting in the edge of the nozzle outside will divert the stream from the vertical, and cause it to splash on the sides of the ingot moulds, but generally a sharp-pointed bar and a skilful man will remove this.

Running Stoppers.—In the event of a running stopper—*i.e.*, a stopper which refuses to shut close—little can be done except to move the ladle as rapidly as possible from mould to mould, and to see that the pitmen remove the scrap from the top edges of the moulds the moment they can get near. In the case of metal partially setting in the nozzle, it may often be removed by one man holding a sharp-pointed bar, with end bent up at right angles, under the nozzle, while another drives it into the nozzle with a sledge, and then rapidly knocks it out again. This is one of those practical things which must be done very quickly and skilfully if it is not to do more harm than good, and is a distinctly dangerous operation for a clumsy man to attempt. If this is not successful, the only thing to do is to remove the nozzle-box on the bottom of the ladle, and knock the nozzle out, when the steel must be caught in the moulds as best it can. This is rarely successful, and frequently ends in spoiling several moulds by covering them with molten steel, and it is generally better to tip the ladle and pour the steel into one corner of the pit. These accidents rarely occur in a well-managed works, but even under the best management they will sometimes happen, and appliances must always be at hand to clear the pit rapidly as soon as the steel has set. When the steel is once in the ingot moulds, if it shows any sign of rising in the moulds, as it frequently does in the case of "dead soft" steel, the sooner the moulds are "stoppered down" the better. Sand and a steel plate held down by a bar through the "lugs" on the mould, secured by wedges, will do this very effectually, and this is the usual plan in most works. If the steel is

quiet in the moulds, there is no necessity to "stopper down" at all, a piece of steel sheet or thin plate placed on the top of the molten metal to cool the surface being quite sufficient. Directly the ingots have set, which will take from three to ten minutes, according to their size and the grade of the steel (whether high or low Carbon), the wedging down plates are removed, and the ingot moulds are stripped off the ingots by lifting them with the ingot crane. Where casting on cars is in use, the bogies are taken away direct to the "stripper." In cases where the ingot refuses to leave the mould after a few blows with the sledge-hammer, and where there is no stripper, it should be put on a bogie and taken to the sticker press. This is simply a powerful hydraulic machine, which is really a primitive form of "stripper," by which it has been replaced at all modern works. During the teeming of the heat, a small sample is usually caught in a hand ladle and poured into a cast-iron mould, and is known as the "pit sample." This is taken to the smiths' shop and drawn down to a bar about 0·75 square inch, a piece cut off one end and welded to the other. To make sure that the weld is sound, a hole is often punched in the weld, and this is enlarged by drifting. If the steel stands this test (see p. 328), it may be considered satisfactory as regards welding. The other end of the bar, after cooling, is bent over an angle block with a radius one and a-half times the thickness of the bar, and for dead soft steel it should bend through an angle of 180°. The sample is then sent to the laboratory for analysis.

The pit is now reset with ingot moulds to be ready for another charge. Before replacing the moulds it is usual in most works to dip them in a deep bosh or tank containing a thin wash of fireclay and blacklead, which protects them to some extent from the cutting action of the molten metal, and also largely prevents the ingots from sticking. Before "boshing," the moulds should be as cool as possible, as if plunged into the wash hot, they are liable to crack, and anything approaching rapid water-cooling should be avoided.

The ingots, on removal from the moulds, are either transferred direct by one of the ingot cranes to a soaking pit, or vertical re-heating furnace near the casting pit, or placed on a bogie and taken to vertical or horizontal re-heating furnaces nearer the mill, according to the arrangements for re-heating at the particular works.

CHAPTER II.

BASIC PROCESS.

Introduction.—For many years before its solution by Sidney Gilchrist Thomas, the question of dephosphorising iron in a Bessemer converter had attracted the attention of leading metallurgists both in England and on the Continent. So far back as 1860, when the Bessemer process was first being introduced on the Continent, Tunner, of Leoben, suggested the use of burnt Magnesite as a lining for converters, although at that time his suggestion had no connection with the dephosphorising problem. Wedding and others also proposed lining the converter with Oxide of Iron or with Bauxite, and Lencauchez recommended the manufacture of bricks from burnt lime with some fritting material. Mr. Snelus, in 1872, took out a patent for the manufacture of basic linings from a mixture of lime and magnesia, with a small quantity of clay and Oxide of Iron as a binding material, and Grüner, in his metallurgy published in 1875, suggested calcined Dolomite, with clay, as a binding material. Mr. Snelus and various other investigators were undoubtedly working in the right direction, but from various reasons had failed to make a basic lining a *practical* success.

The Thomas-Gilchrist Experiments.—It was at this stage that Mr. Sidney Thomas brought his great abilities and indomitable energy to bear upon the problem which he ultimately solved so successfully and completely. Having first most carefully studied the question in all its bearings from a theoretical standpoint, he came to the conclusion that the non-removal of Phosphorus during the ordinary Bessemer blow was due entirely to the silicious nature of the slag formed, and that the essential condition for dephosphorising was the formation and maintenance of a basic slag. This, then, was the problem he set himself to solve. It was clear that it was impossible to maintain a basic slag in a vessel lined with silicious material, and therefore the first thing necessary was to obtain either a neutral or a basic lining, in which basic materials could be kept in a fused condition without fluxing it away. After many attempts, under the greatest possible difficulties, this was successfully accomplished by using burnt lime, or burnt Dolomite, mixed with some binding material like Silicate of Soda, argillaceous clay, &c., and with the assistance of his cousin, Mr. Percy Gilchrist, numerous charges of pig-iron, weighing only 8 lbs. each, were dephosphorised in a small toy converter. Step by step, as experiments became possible on a larger scale, the lining was improved, the advantages of additions of lime during the blow, and the necessity for an after blow to remove the Phosphorus, were discovered, and the basic process, as we know it to-day, became an accomplished fact.

The first patent is dated November, 1877, and was for the manufacture of bricks from pulverised lime, with Silicate of Soda as a binding material, other materials also being claimed for the same purpose. The bricks were to be moulded, dried, and afterwards kilned at a high temperature, and the next step was the substitution of aluminous clay for the Silicate of Soda as a binding material. These bricks were made as follows:—Magnesian Limestone, free from Silica, was burnt, finely ground, mixed with 3 to 4

per cent. of good fat fireclay, kneaded with a little water, made into bricks, and burnt at a high temperature; the distortion, however, was so great that they could not be used, and regrinding and remoulding had to be resorted to. The shrinkage of the bricks, varying from 25 per cent. to 50 per cent. of their volume, was a very serious drawback, and many attempts were made to get over this by using pure Magnesia, but the cost greatly militated against its use. Finally these difficulties were overcome by first burning Magnesian Limestone at a very high temperature, to shrink it completely, and then using anhydrous tar or some Hydrocarbon as a binding material, and heating the bricks thus made in closed moulds at a comparatively low temperature sufficient to just coke the tar.

During the early experiments, the inventors were extremely fortunate in interesting Mr. E. P. Martin in their work, and he not only gave them great facilities for carrying out their experiments on a larger scale, but assisted them alike financially and by his business and technical experience. Later on, Mr. Windsor Richards, who was then manager of Messrs. Bolckow, Vaughan & Co., arranged with Mr. Sidney Thomas to try the process on a large scale. It was at these great works at Middlesbrough that the commercial value of the process was proved, and that Thomas and Gilchrist were fortunate enough to obtain the assistance of Mr. J. E. Stead, who rendered them great service in helping to surmount the numerous difficulties that arose before its success was finally assured.

Both Mr. Edward Riley and Mr. Snelus held certain patents bearing on basic bricks and linings, and as it was felt that these gentlemen had certain claims, all parties agreed to submit these to arbitration, with the result that both Mr. Snelus and Mr. Riley became interested in the English patents, the foreign being entirely retained by Messrs. Thomas and Gilchrist.

Basic Bessemer Plant.—The plant employed in the basic Bessemer process differs very little from that used in acid or ordinary Bessemer, such differences as exist being only in matters of detail. The converter is exactly the same, the concentric form already described on p. 6 being often employed, as it enables a larger quantity of metal to be blown in a given sized vessel, and also enables the slag and the metal to be poured off at opposite sides, if desired.

The Lining of the Converter.—The essential difference between the two processes consists in the material used for the refractory lining of the converter, the silicious material used in the ordinary Bessemer process being replaced by a lining of shrunk Dolomite, known as basic material, rammed with anhydrous tar. This lining, together with lime additions made during the blow, allows of the formation of a Phosphate of Lime which is not decomposed by metallic iron at the high temperature of the converter, and thus practically the whole of the Phosphorus present in the iron is removed in combination with the lime in the slag.

Preparation of the Basic Material.—Shrunk Dolomite or basic material is prepared as follows:—A pure Magnesian Limestone, containing not more than 2 per cent. of Silica, should be selected, and the following analyses may be taken as fairly typical of the raw and burnt stone (see tables on next page).

This raw stone is broken into pieces which will pass through a 3-inch ring, and burnt at a very high temperature, preferably in a cupola, lined within a few feet of the charging hole with basic material. Very good material has been made in kilns specially constructed for the purpose, but in practice a basic-lined cupola has been found to give the best results.

The usual method of lining the cupola is to ram it with ground basic material mixed with tar, a collapsible core similar to that used for

ramming a converter being used. The cupola having been thoroughly dried, is well charged with coke and blown up, and then alternate layers of coke and broken Dolomite are charged in the usual way, until the cupola is full to within a foot or so of the charging door. At the bottom is a raking-out door. Every two hours such material as has passed below the twyers is raked out. For the first few hours the stone will be very imperfectly burnt, and the greater part will have to be returned to the cupola, but in a short time the furnace will get into working order, and the charging and withdrawing will go on continuously. There is always a certain percentage of the stone which is imperfectly burnt, but this is easily detected by its appearance, and is picked out by hand and returned to the furnace. The temperature of the cupola has to be regulated carefully, as it is quite possible, by using too much coke and too high a pressure of blast, to frit the shrunk stone into a solid mass, when its withdrawal without stopping the cupola entirely is a matter of the greatest difficulty, if not an impossibility.

Dolomites or Magnesian Limestones.

				From Whitehaven Quarry, Porthywaen, Llynclys.			
Silica,	1·72	1·10	1·26	0·9	0·30	0·30	1·10
Oxide of Iron and Alumina,	2·30	1·64	1·80	1·30	1·20	1·19	1·14
Lime,	33·52	34·20	35·00	31 0	33·3	32·9	31·42
Magnesia,	20·05	19·60	19·40	20·6	18·75	19·02	20·00
Carbonic Acid,	42·20	43·30	42·40	46·34	46·60	46·50	46·2

Calcined Dolomite.

			From Whitehaven Quarry.
Silica,	1·66	2·50	1·40
Oxide of Iron and Alumina,	4 80	3 99	3·15
Lime,	56·50	57·32	57·30
Magnesia,	35 83	34·95	37·38
Loss on ignition,	1·06	1·00	0·60

The best results are probably obtained with a blast pressure of 1 lb. at the blower and a consumption of 570 to 670 lbs. of coke per ton of raw stone charged. In most English works it is not usual now to shrink the Dolomite on the works, but it is found to be cheaper to buy the shrunk stone from firms who make a special business of preparing it. It must be carefully stored and protected from moisture, and a large stock should never be kept on hand, as under the best possible conditions it soon absorbs moisture, and rapidly deteriorates. The sooner, therefore, it can be used after shrinking the better. The shrunk material is ground, generally in a good pug mill with edge runners, until the largest lumps are not bigger than large peas, and the remainder is much finer; it is then well mixed with the required amount of well-boiled hot tar, often in the same mill. It

is important to have the tar well boiled to expel moisture; it should be used fairly hot so that it is quite fluid, and just sufficient should be added to enable the material, when rammed and pressed, to bind well together.

Brick Linings.—In the early days of basic practice it was usual to make bricks by ramming the material with red-hot iron rammers into wrought-iron moulds of different shapes and sizes to suit the sweep of the converter. The bricks were usually about 12 by 9 by 6 inches thick, and were baked at a very low heat in the moulds, and allowed to cool in the stove. When cold, the bricks were removed from the moulds by knocking out the cotter pins (shown in fig. 69), and subsequently built up in the converter.

These hand-rammed bricks are not much used now, the usual practice being to mould the bricks in hydraulic presses, placing them in position in the converter as they come from the press *without any baking*. In this case it is customary, and gives good results, to build up the first three or four courses at the bottom of the converter with hard-baked bricks, and the other part with green bricks. As each course of bricks is laid, a backing of 3 or 4 inches of basic material is rammed hard between the bricks and the shell of the converter, the bricks being laid close together without any jointing material. Bricks green from the press are said to give equally good, if not better, results than baked ones, as when the vessel is gradually warmed up all the joints unite better and form a continuous lining. In the first machines designed a pressure of about 3,000 lbs. per square inch was employed, but Mr. Joseph Colley has found that a pressure of about 500 lbs. per square inch gives equally good results.

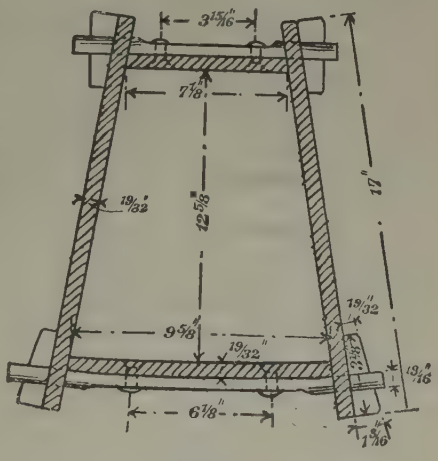


Fig. 69.—Iron Mould for Hand-rammed Basic Brick.

Ramming the Linings.—Another method of lining, and one which, perhaps, when labour, costs, and other matters are taken into consideration, gives the best results, is to ram mixed basic material with hot iron rammers between a plug or taper core and the shell of the vessel, exactly in the same way as described for ramming an acid vessel with ganister (fig. 12, p. 8). The converter for this purpose is usually inverted, lifted out of its trunnions on to a special carriage by means of the hydraulic ram underneath, and taken to the basic repairing shop, where the re-lining can be more conveniently done than when it is in its usual position. This removal of the converter for re-lining is simply a matter of convenience, and in many cases the converter is never removed from the Bessemer shop.

Although shrunk Dolomite is now almost universally employed, very good bricks were made in the early days of basic practice from shrunk lime, both at Witkowitz and Kladno. The following is an analysis of Witkowitz limestone, the Kladno stone being similar, but free from Magnesia; when burnt it contains from 5 to 6 per cent. Silica:—

WITKOWITZ LIMESTONE.*

Lime,	47·46 per cent.
Magnesia,	2·93 ,,
Ferrous Oxide (FeO),	3·41 ,,
Manganese Protoxide (MnO),	0·29 ,,
Carbonic Acid,	42·85 ,,
Silica,	2·48 ,,
Alumina,	0·53 ,,

The Bottom Section and Plug.—The bottom section of the converter in basic Bessemer practice is very similar to that used in the ordinary acid process, the essential difference being that basic material is used instead of ganister for the refractory material. The plug or centre portion containing the twyer holes also differs, as instead of having baked fireclay twyers containing the blast-holes fixed in the plug, these passages for the air blast are made by ramming the basic material round a number of wrought-iron taper pins or rods, and afterwards withdrawing these, and so leaving a series of holes. A cast-iron plate (fig. 71) containing the required number of holes is used, and through each hole a wrought-iron rod or pin, about 4 inches longer than the depth of the plug, is passed, having a boss on the end of each pin to prevent its passing quite through the plate. A wrought-iron casing (fig. 70) about 2 feet 6 inches deep, according to the thickness of the plug required, is now cottered round the cast-iron plate, and the whole casing is rammed up with the tar-mixed basic material, special care being taken to ram the material hard round each rod or pin. A rammer, with a hole in the head for the pin to pass through, is used for this purpose.

When the casing is rammed full, the entire plug is suspended from a crane, and the pins knocked out by sharply striking their projecting ends. As they are all made with a fair taper there is no difficulty about this. The bottom-plate in the plan and elevation, with the twyer pins ready in position and the wrought-iron casing ready for cottering on, is shown in fig. 71. E and F are rammers for ramming the basic material. The plug, with the casing still on, is now taken on a trolley to a special oven, where it is very carefully heated, the temperature being gradually raised. One form of oven is a long furnace with two or more sets of parallel rails, so that two or more plugs can be introduced side by side. The fireplace is practically in the centre, so that this is the hottest part of the furnace, and each end of the furnace is comparatively cool. The trolleys on which the plugs rest are put just inside at first, and gradually pushed forward until they reach the hottest part, where they are kept until completely baked, and are then gradually pushed towards the other, and comparatively cool end, from which they are withdrawn. It is very important not to withdraw them too hot, as during cooling in the atmosphere, especially in damp weather, moisture is rapidly absorbed.

At the North-Eastern Steel Works these plugs are made by a special hydraulic press, all hand-ramming being dispensed with, and they are said to stand better and last a greater number of blows.

Instead of using iron rods to make the holes, fireclay twyers, rammed round with basic material, may be used as in the acid Bessemer practice, and these give very fair results, less metal being ejected from the converter than with the ordinary pin-hole plug.

The thickness of the plugs varies from 16 inches to 20 inches, and the number and size of the holes are different at almost every works as the following table shows :—

* Wedding, *Basic Process*, p. 47.

The North-Eastern Steel Co.,	101 holes, $\frac{5}{8}$ inch diameter.
Hickmans, Ltd.,	60 holes, $\frac{1}{16}$ to $\frac{3}{16}$ inch diameter.
* Witkowitz,	35 holes from $\frac{1}{2}$ to $\frac{11}{16}$ inch diameter.
* Rotheerde,	64 ,, ,, $\frac{5}{16}$ inch diameter.
* Kladno,	84 ,, ,, $\frac{3}{8}$ inch diameter.

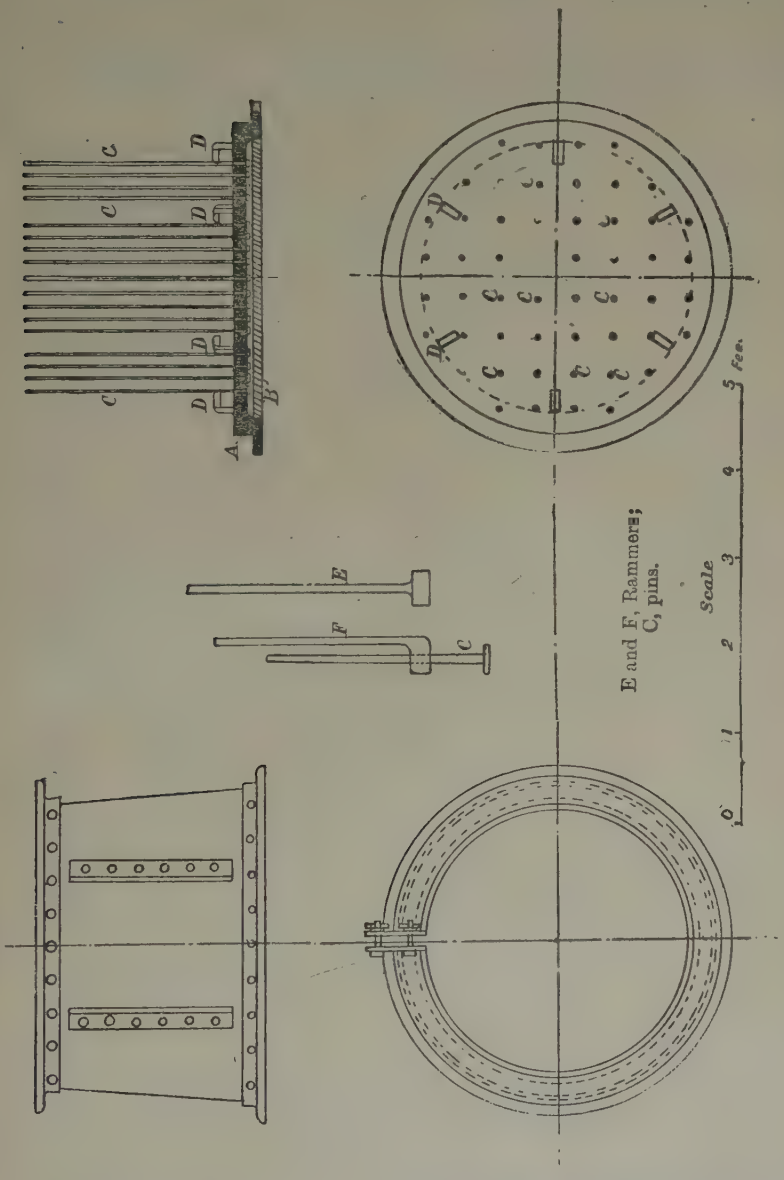


Fig. 71.—Plan and Elevation of Bottom-Plate, with twyer pins in position ready for iron casing to be fixed round previous to ramming.—D, Lugs on bottom-plate to hold basic material; C, pins.

Fig. 70.—Plan and Elevation of Wrought-Iron Casing for fastening round bottom-plate.

* Wedding, *Basic Process*, p. 75. This was their practice some years ago, and probably, with larger converters, they now have greater total twyer area. The particulars at other works represent present practice.

In preparing the bottom section, the baked plug is removed from the furnace, the casing taken off, and the bottom section dropped over it as shown in the sketch (fig. 72), and the space between the two is well rammed with basic material. The bottom section is then ready for fixing on the converter.

The method of fixing on the bottom section to the converter is similar to that in vogue in the acid practice, the only difference being that instead of moist ganister, basic material with excess of tar is used to make the joint between the bottom section and the body of the converter.

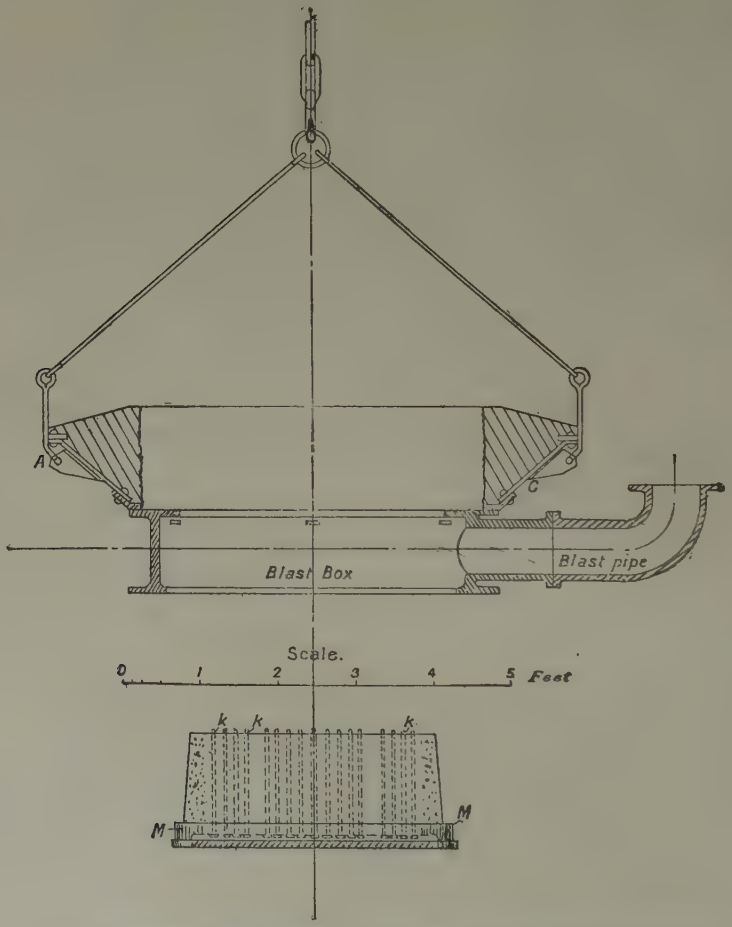


Fig. 72.—Sketch showing method of inserting rammed baked twyer plug in bottom section of the converter.

The tar should be mixed with shrunk Dolomite until it has the consistency of very soft india-rubber; it is then spread all round the circumference of the bottom section, and the latter is pressed hard by the hydraulic ram against the converter, and cottered on to it in the usual way.

Disposition of Plant.—The general arrangement of converters and cupolas, as also of the casting and ingot cranes, is exactly the same as already described for acid work, the only two points that require special attention being facilities for conveying large quantities of lime to the converter, and for removing the large quantities of slag produced. The former is usually shot down a shoot from an overhead platform above the converter through the nose of the vessel, which is brought underneath the shoot by rotating it to the proper position. By this arrangement lime can be added in the required quantity at any time by turning the vessel down for a few seconds only.

In some works the lime is conveyed to the converter in a special carriage, which travels on the converter platform. But this is not to be recommended, as the lime carriage cannot be run backwards and forwards during the blow without interfering with other operations, and if further additions of lime are required, either during the ordinary or the after blow, these have to be thrown in through the nose of the vessel.

Removal of Slag.—The removal of the slag is effected in various ways. In some works it is poured from the converter on to the pit floor on the same side as the steel casting pit, watered to cool it, broken up with bars, and wheeled away in iron barrows while still red-hot.

In other works it is poured off from the converter either on the same side as, or on the side opposite to, the casting pit, more generally the former, into large iron bogies running on rails. When one or two heats have been poured, the bogie is drawn away by a small locomotive to the slag-house for grinding.

The slag from all basic Bessemer works is now always ground to the finest powder for manure, and this method of removing it in bogies is much to be preferred, as it keeps the casting pit free from slag and steam, and costs less. Although it is more dense and compact than when poured on the ground, there is no great difficulty in breaking up these slag balls into sizes suitable for fine grinding in the mills. If the slag is deficient in lime, or contains an excess of Silica or Oxide of Iron, it may form dense, hard masses, somewhat difficult to break up, but if of normal composition there is no serious trouble in this direction.

Description of the Process.

The converter having been thoroughly heated, either from previous charges or by means of a coal or coke fire blown up by the blast, about 3 to 4 cwts. of lime per ton of metal to be blown, are shot in from the overhead shoot, and the molten metal from the blast furnace, mixer, or cupola is at once poured into the vessel, the blast turned on, and the vessel rotated into the vertical position. The various stages of the blow are very similar to those described in the preceding Chapter, but during the boil even larger quantities of slag are ejected from the vessel than in the acid blow. The difference between the processes is not very noticeable until the flame drops, indicating the complete removal of Carbon. Instead of turning the vessel down and stopping the blast, as in the acid process, blowing is continued for some three or four minutes longer. This is termed the after-blow, and it is during this period that practically all the Phosphorus is removed. It is frequently necessary to add more lime during this after-blow, the length of which varies with the percentage of Phosphorus and Silicon in the pig-iron, and, to some extent, with the temperature of the bath of metal. If the Silicon much exceeds 1 per cent., it not only increases the length of the after-blow by raising the temperature of the

bath, but it combines with the lime, and thus makes the slag less basic, further retarding the removal of Phosphorus.

In some works, hammer scale, tap cinder, or briquettes made of iron oxide, hammer scale, &c., with lime as a binder, are added during the blow; briquettes made of Manganese ore are also used. The effect of these is to reduce the quantity of scrap, and in some cases the final lime additions, and to produce a fluid oxidising basic slag which oxidises the Phosphorus to some extent during the earlier part of the blow, and thus shortens the "after blow."

In basic practice, to insure a steel of uniform quality, it is of the greatest importance that the pig-iron should be of regular composition, and hence the great advantage of using a mixer or receiver (p. 15), or carefully selecting the metal and re-melting in a cupola. The Silicon should not, to give the best results, exceed 1 per cent.; best practice in England is obtained with about this percentage of Silicon and from 2·5 to 3·0 per cent. Phosphorus, although metal as high as 4 and as low as 2·14 per cent. Phosphorus has been regularly used in some cases.

In most works the mixer metal is used either alone or with a certain proportion of selected iron melted in the cupola, and probably the combination of metal mixer and cupola gives the best results as regards regularity of make. Although metal of regular composition is of the greatest importance for economic work and production of steel of regular quality, it must not be supposed that it is impossible to make basic Bessemer steel from pig-iron containing more than 1 per cent. of Silicon, as many thousands of tons in this country are made every year from pig-iron containing 2 per cent., or even more, and probably the great bulk of basic pig-iron used contains 1·5 per cent.; but, provided the pig-iron is low in Sulphur, there can be no doubt that it is a great advantage in every way when Silicon does not exceed 1·0 per cent.

Sampling the Metal.—Given a pig of regular composition, even if somewhat silicious, the heat of the bath will vary very little in different charges, and a good blower will be able to judge the length of the after-blow to within 30 to 40 seconds. The after-blow is usually continued for a given time for normal metal, the vessel then turned down, and a sample taken with a hand ladle through the nose of the vessel and poured into a cast-iron mould. This, immediately it has set, is taken to a small steam hammer, hammered till about $\frac{1}{2}$ inch thick, quenched in water, and broken with an iron bar over a V-shaped anvil block.

The blower judges from the fracture the percentage of Phosphorus present, and decides whether it is necessary to add more lime before continuing the blow. Very frequently the charge will not require more than another 30 seconds blowing, and the vessel will be turned up for this time, when another sample is taken and examined by fracture before making the Manganese additions. An experienced blower, working with good metal, rarely has to take more than two samples besides the final one, and generally only one; he can detect by the fracture the difference between 0·06 and 0·07 per cent. of Phosphorus in the steel, and very seldom makes a mistake in judging the percentage of Phosphorus present. The fracture of a high Phosphorus sample is very characteristic, long bright crystals interspersed in the material being very noticeable, while, when the Phosphorus is practically all removed, the sample has a fine close granular structure, and the outside edges are smooth. If much Sulphur is present in the metal, the appearance of the fracture is very different from metal free from Sulphur; the characteristic long Phosphorus crystals are masked somewhat, the fracture is dull and non-crystalline, and the outside edges of the sample crack and have a rough appearance.

The blower being satisfied with his sample, the slag is poured off as far as possible and the Ferro-Manganese, &c., added, the steel allowed to stand for a few minutes, and then poured into the casting ladle and teemed into ingot moulds. Although it is most desirable to have a pig-iron of regular composition, still with practice it is extraordinary how steel of great regularity is made even from very variable furnace metal. But, with the greatest care and experience, the losses caused by occasional high Phosphorus steel, and cold heats, and the wear and tear on the converter linings, are so great that they cost probably far more than it would do to make a pig-iron of the required composition.

Addition of Ferro and Spiegel, &c.—The addition of Ferro-Manganese is usually made in the vessel, and not in the ladle; when low Carbon steel is required, it is generally broken to pass through a 4-inch to 6-inch ring, and heated to a red heat in a special furnace.

It is a common practice to add some hematite iron or low-grade spiegel or Silico-spiegel before the Ferro, as this assists in the deoxidation of the metal, and so saves the Ferro. For mild steel 80 per cent. Ferro-Manganese is generally used, although probably 70 per cent. is more economical, as the higher the percentage of iron in the Ferro the less tendency there is for the Manganese to pass into the slag. A small percentage of Phosphorus always passes back from the slag into the metal, on adding these Manganese alloys, owing to the reducing action of the Carbon and of the Manganese; and the blower has always to allow for this, and blow the metal down, so that the Phosphorus is somewhat lower in his final sample than is required in the finished steel. Provided the slag is sufficiently basic, the amount passing back should rarely exceed 0·02 per cent., and is generally less.

When high Carbon rail steel is required, this can be made by adding molten spiegel in the ladle, or by recarburising the metal by the Darby or some similar process (see pp. 102 and 189). The difficulty is to keep the slag back from the ladle; for although this is always poured off from the converter as much as possible before transferring the metal, some always remains behind and passes with the metal into the ladle.

The CO evolved on the addition of Ferro or spiegel always causes a violent agitation of the bath, and brings slag and metal into contact, and thus, apart from any direct reducing action, facilitates the reduction of the Phosphorus. To avoid this reaction as much as possible, it is customary in some works to use Silico-spiegel, high in Silicon and low in Carbon, of which the first three analyses following are examples:—

Carbon.	Silicon.	Manganese.		Carbon.	Silicon.	Manganese.	
1·74	9·76	30·14	Low Carbon.*	4·55	3·35	48·20	High Carbon.
2·13	8·81	28·89	Low Manganese.	5·79	0·43	68·74	High Manganese.
3·65	4·58	27·13	High Silicon.	5·59	0·12	70·10	Low Silicon.

It will be noticed that, in Ferro Manganese, the Carbon and Manganese increase, and the Silicon decreases, as illustrated by the last three analyses.

The amount of Manganese "additions" required for dead soft steel will vary greatly with the pig metal used, and according to whether this is high or low in Manganese, Silicon, and Phosphorus.

If the metal contains about 1 per cent. of Silicon and 2 per cent. of Manganese, from 0·2 to 0·35 of the latter will be left in the bath after the completion of the after blow, and, consequently, less Manganese will have to be added. On the other hand, if the metal is very silicious and low in

* Wedding, *Basic Bessemer Process*, p. 98.

Manganese, it will blow very hot, there will be a tendency to over-oxidation, and more Manganese additions will be necessary.

Assuming *no* Manganese to be left in the blown metal, and that *all the Manganese added passed into the bath*, a 10-ton charge of steel would require 140 lbs. of 80 per cent. Ferro to give 0·5 per cent. Manganese in the finished steel, as can be seen from the following calculation :—

200 cwts., or 10 tons, of metal require 1·0 cwt. metallic Manganese to give 0·5 per cent.

To yield 1·0 cwt. of metallic Manganese, 1·25 cwts. or 140 lbs. of Ferro containing 80 per cent. Manganese are required ; 1·25 cwts. or 140 lbs. distributed over 10 tons, give 14 lbs. of Ferro required per ton of metal.

This calculation is based on the assumption that no Manganese is left in the blown metal, but as from ·10 to ·20 nearly always remains, less than this quantity should be required. As a matter of actual practice, however, owing to some Manganese being oxidised by Oxides in the slag, and some by the Oxide left in the bath of metal, a considerable amount of the added Manganese is lost in the slag, and instead of 14 lbs. per ton being required, 18 to 20 lbs. is about the usual quantity required, and sometimes as much as 25 lbs. per ton of metal *charged* is added, which is considerably more than 25 lbs. per ton on the metal left in the converter.

CHAPTER III.

MANUFACTURE OF STEEL IN SMALL CONVERTERS.

Survival of the Small Converter. — Notwithstanding the almost universal tendency to increase the capacity of converters, and the general adoption of bottom blowing in rotating converters, the small converter, both fixed and rotating, is still in use in Sweden, in this country, and in America, and under special conditions, where small outputs only are required, very satisfactory results are obtained. These converters may be divided into two classes, fixed and rotating; and while the former are all, of necessity, side blown, the latter may have twyers either through the bottom, or arranged in different ways round a part of the circumference. The small bottom-blown converter is confined almost entirely to Swedish practice ; the other converters, most of which are named after the designers or patentees, being used to produce either very soft, low Carbon steel, or more especially steel for the manufacture of castings.

The Swedish Bessemer process, Clapp Griffiths, Robert, The Walrand Legénisel, and the Tropenas processes, which it is proposed to describe, vary more as to shape of the converter, arrangement of twyers, valves for regulating the blast, and other details, than in any essential differences in the processes themselves.

The Swedish Bessemer Process.—To Sweden belongs the honour of having first carried out the Bessemer process on a commercial scale, and in considering the manufacture of steel in small converters, the process, as carried out in that country, will be first described.

The earliest form of converter used in Sweden was the fixed converter, similar to that shown in fig. 73, except that the body was carried on masonry foundations instead of being supported on cast-iron columns, but for more than 35 years rotating converters have been almost exclusively

employed. The converters are generally about 4·92 to 5·25 feet in diameter at the widest part, and 3·94 to 4·26 feet at the bottom, while the interior varies in height from 6·56 to 8·2 feet. They are made with as small a mouth as possible, generally about 8 to 10 inches in diameter, for the better preservation of the heat of the metal. The amount of metal charged is generally from about 3 to 3¾ tons of pig-iron, and the pressure of the blast varies from 7·8 to 9·6 lbs. per square inch. The twyer area is usually from 4·65 to 5·43 square inches per ton of metal, the total area varying from 12·4 to 18·6 square inches in different converters. The twyers are divided up into from 70 to 200 holes generally from 0·35 to 0·39 inch in diameter, but sometimes as small as 0·25 inch, or as large as 0·59 inch.* A very large twyer area is found to be of special importance in blowing these small charges, the pressure of the blast being of very secondary importance provided it is sufficient to keep the metal out of the holes. In the early experimental days Sir Henry Bessemer was of opinion that high pressure of blast was the important factor, and it was not till G. F. Goransson adopted a large twyer area, thus securing an abundant air supply with corresponding shortness of the blow, and, at the same time increasing the temperature of the bath, that successful results were obtained; previous to his experiments the metal was generally too cold to cast satisfactorily into ingots.

The pig-iron used is always low in Silicon, usually about 1·00, and generally high in Manganese, frequently containing 3 per cent., and often 4 to 5 per cent. of this metal. Typical analyses of Swedish Bessemer pig are given in Table v.

TABLE V.—Analyses of Swedish Bessemer Pig-Iron.

Combined Carbon,	1·13 per cent.	1·42 per cent.
Graphite,	3·23 ,,	2·99 ,,
Total,	4·36 ,,	4·41 ,,
Manganese,	2·98 ,,	3·06 ,,
Silicon,	0·95 ,,	0·97 ,,
Phosphorus,	0·019 ,,	0·019 ,,
Sulphur,	Trace	Trace

The universal practice is to take the metal direct from the blast furnaces, which, owing to the great care taken in charging and working, produce a pig of very regular quality. Instead of blowing until the metal is completely decarburised, and adding Spiegeleisen, Ferro-Manganese, &c., which is the usual Bessemer practice in most countries, it is customary in Sweden to blow until the required degree of decarburisation has been reached, which is judged by the appearance of the flame. In the case of the higher carbon steels, the character of the sparks is the chief guide, although before pouring into the ladle, the converter is usually turned down and a sample hammered out and examined for fracture, after which a few seconds extra blowing may or may not be given as required. Very large quantities of steel are made in Sweden without any additions of Ferro or Spiegel at all, the metal with, say, 0·3 to 0·5 per cent. Carbon retaining from 0·2 to 0·35 per cent. of Manganese at the end of the blow. Where dead soft steel is required with 0·15 per cent. of Carbon and under, small Manganese additions are usually made.

The Manganese in the pig-iron plays a most important part in Swedish practice, as besides increasing the temperature of the bath, it increases the

* Akerman, *Trans. American Mining Engineers*, vol. xxii., p. 276.

fluidity of the slag, tends to remove Sulphur from the metal, and protects the bath from over-oxidation. It has, on the other hand, a cutting action on the lining, and decreases the life of bottom and twyers, and, as it all practically passes into the slag, the waste is increased; but the other advantages probably more than compensate for these drawbacks. The waste in Swedish practice varies with the grade of steel produced, being from 9 to 10·5 per cent. for high Carbons, and for low Carbon steel, made from Manganiferous iron, as high as 12 to 12·5 per cent. Owing to the coldness of the metal, due to low Silicon, small charges, and not very rapid work, there was, in the early days, considerable skulling in the ladle, but this has been largely obviated by the use of Caspersson's converter ladle, introduced in 1880. This consists of a narrow ladle furnished with the ordinary stopper and nozzle for teeming, but having at one side, near the bottom, a lateral opening which is the same size as the mouth of the converter, and to which it can be securely and tightly fixed by cotter pins, a fireclay joint being made between the ladle and the nose of the vessel. When the blow is finished the converter is turned down, the ladle swung round on a crane, and fastened on to the mouth of the converter. The converter is then turned down a little more, so only a small portion of the metal flows into the ladle, the rest remaining in the vessel. By this means the metal can be allowed to stand for a reasonable time to permit gases to escape without any fear of chilling, and as the depth of metal in the ladle can be kept low, there is less head of metal when teeming, and consequently the stream passes more slowly into the ingot moulds, both of which conditions tend to produce metal free from blow holes. In some works it is usual to add a little aluminium to the charge before or during teeming to increase the solidity of the ingots. When the Caspersson ladle is used the ingot moulds are carried under the ladle on cars, or on a turntable. In the case of hot blows occurring, owing to the small mouth of the converter, and the small charges worked, scrapping is difficult, and Mr. Caspersson finds, according to Professor Akerman, that finely-crushed ore added during the blow gives very satisfactory results, as besides the direct chilling there is the absorption of heat due to the reduction of the Oxide of Iron. The high quality of the Swedish product is due to the very regular composition of the pig-iron used, to its great freedom from Sulphur and Phosphorus, and its high Manganese content, and also to the smallness of the charges worked. The regular composition of the pig-iron and the small charges mean a low and regular temperature in the finished steel, and are most important factors in producing metal free from blow holes and red shortness.

Some fixed converters are still used in Sweden and are usually about 4 feet in diameter, holding from 25 cwts. to 2 tons, and having about 20 twyers, with one hole $\frac{7}{8}$ of an inch in diameter, arranged round the circumference at equal distances apart. The twyers are usually horizontal, but instead of pointing to the centre of the vessel are sometimes slightly inclined from the centre, with the object of giving rotation to the molten metal during blowing. This arrangement of the twyers has now, however, been practically given up, owing to the rapid wearing of the linings due to the abrading action of the metal. The blast-box may either be a belt round the vessel with branch pipes to the twyers as in an ordinary cupola, or form part of the converter bottom, each twyer being connected with this. The vessels are all acid lined, and about 6 to 7 lbs. pressure of blast is used.

When the blow is finished the steel is tapped out through a tap-hole, which is opened in the usual way with an iron bar, otherwise the same practice is adopted as in the case of rotating converters.

The following may be taken as typical analyses of *high-class* Swedish steel of all grades of Carbon made by the Bessemer process from 0·10 to 1·30. The Sulphur is given as "trace to 0·005 per cent.," and although occasionally it will be a little higher than this, it rarely exceeds ·010 per cent.·—

TABLE VI.—General Analyses of Swedish Bessemer Steel.

Carbon.	Manganese.	Silicon.	Phosphorus.	Sulphur.
0·10	0·16	0·008	0·028	Trace to 0·005 per cent.
0·15	0·18	0·012	0·027	
0·20	0·20	0·016	0·026	
0·30	0·22	0·018	0·026	
0·40	0·24	0·020	0 025	
0·50	0·26	0·024	0·025	
0·60	0·28	0·028	0·024	
0·70	0·29	0·030	0·023	
0·80	0·30	0·032	0·022	
0·90	0·32	0·036	0·021	
1·00	0·34	0·040	0·020	
1·10	0·36	0·044	0·020	
1·20	0·38	0·046	0·020	
1·30	0·40	0·048	0·020	

The Clapp-Griffiths Converter.—This is a fixed side blowing converter very similar to the Swedish form, the chief difference being that the twyers are placed higher, about 8 or 10 inches from the bottom of the converter, and have a valve attachment for partially shutting off the blast from each twyer during tapping to prevent over-oxidation of the metal. There are usually only six twyers, and these are about $1\frac{1}{8}$ inches in diameter. An improved form of this type of converter, patented by Mr. Geo. Hatton, is shown in fig. 73, in which the solid bottom is replaced by a movable one, and a much simpler form of valve is used for partially shutting off the blast. In actual practice these valves are rarely used except in cases of a hard tap. The movable bottoms were a distinct improvement and greatly facilitated repairs. The bottoms have to be removed after about 30 to 40 blows, but the twyers are renewed, as a rule, after every 12 or 15 blows. The vessels are usually rammed with ganister, the bottom sections being repaired in the same way. Burnt fire-brick twyers are used with a slight taper, so that they can be readily put into position. The steel produced is very soft, and with iron of regular composition excellent results are obtained, but the waste by oxidation is very great, being not less than 20 per cent., including cupola loss, and frequently more. The pig used should contain about 2·0 to 2·25 per cent. of Silicon, much less than this giving cold heats, and much more tending to produce wild over-blown metal. This converter is exclusively used for the production of dead soft steel, and it is not adapted for the manufacture of varying grades of Carbon steel. The blow lasts from 12 to 15 minutes, and is similar in all respects to an ordinary Bessemer blow, and immediately the flame drops the metal is tapped into the ladle which stands ready under the tap-hole. When the pig-iron is being run into the converter, and during the tapping of the steel, dense brown fumes, due to the oxidation of the iron, are very noticeable.

The following may be taken as a fair representative analysis of the steel produced :—

Carbon,	0·100
Silicon,	Trace
Sulphur,	0·050
Phosphorus,	0·050
Manganese,	0·400 to 0·600

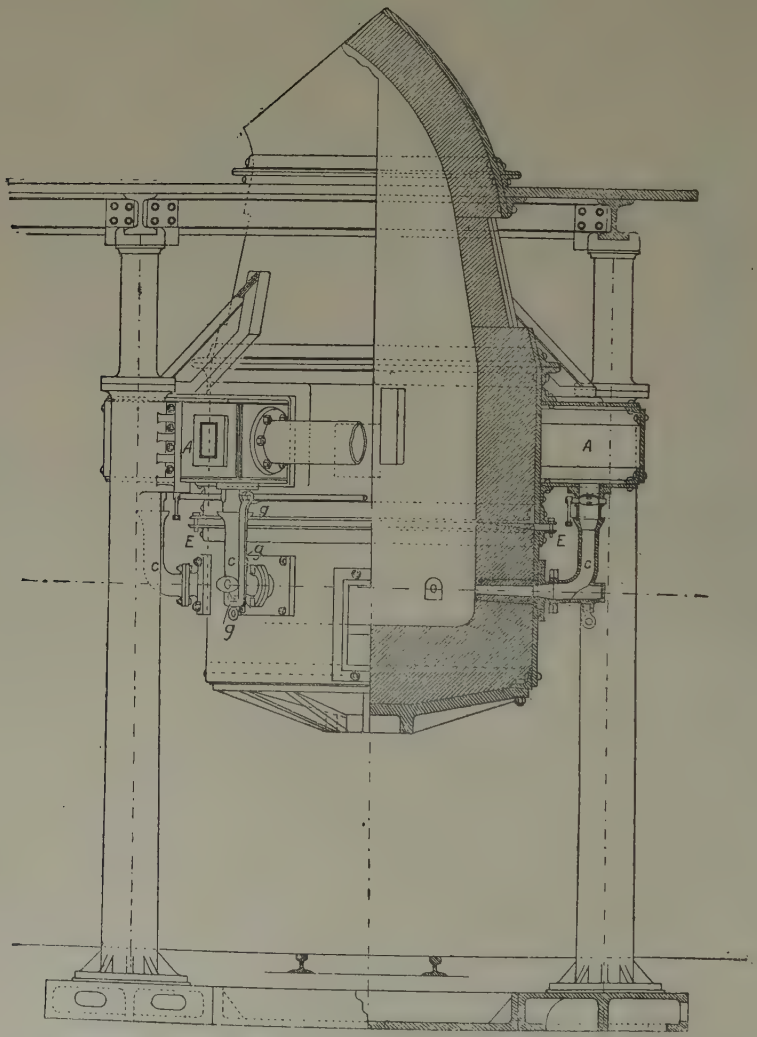


Fig. 73. - The Hatton Fixed Converter, showing movable bottom, which is fixed on the body of the vessel by bolts and cotters at E. The blast belt, A, extends round the entire converter. The branch pipes, C, are connected by a ball and socket joint to the blast belt, and can easily be turned to one side when it is necessary to replace a twyer. These pipes are held in position by a screw and pivoted yoke shown at *g*. There is a hydraulic ram under the converter, which is used for removing and replacing the bottoms.

The Robert Converter.—This is a small tipping converter, with twyers arranged on one side only, and in transverse horizontal section is D-shaped, as shown in the sketch. The twyers are placed horizontally, but are inclined at different angles to the flat side, P, of the converter, which gives a rotary motion to the bath, and brings all parts of the metal successively under the action of the blast, thus causing equal decarburisation throughout the entire mass. The molten metal is poured into the converter in the usual way in sufficient quantity to fill it to just above the twyer level, the blast turned on, and the vessel rotated to the vertical position by any suitable gear. By raising or lowering the vessel, the blast is either blown

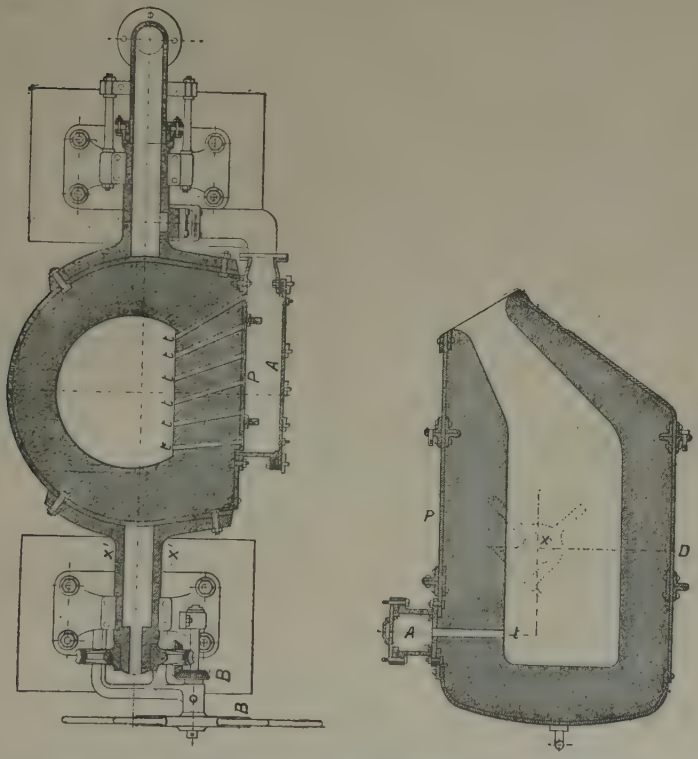


Fig. 74.—Vertical Section and Sectional Plan of Robert Converter, showing the inclination of the twyers on the flat side, P, the blast-box, A, and rotating gear, B, B.

through the fluid iron or made to impinge upon its surface. It is claimed that even while quite vertical the blast does not penetrate the bath, or only the very thinnest layer of molten metal, but forces the metal away from the twyers, so that refining is effected by surface action. The excess of air injected into the twyers is also said to burn the Carbon Monoxide evolved to Carbon Dioxide, thus greatly increasing the temperature of the metal. The pressure of the blast employed is usually about 4 lbs., and this can be regulated at will by means of a valve; and by tilting the converter the resistance to the blast can also be varied, as all the twyers having the same height of metal to support, the pressure on each is the same. The first period of the blow lasts from 7 to 8 minutes, and the second from 3 to 4, when the

flame disappears. Blowing, however, is continued from 1½ to 2 minutes more, during which time the flame re-appears, and then suddenly drops, when the finishing metal, consisting of Ferro-Manganese with or without Ferro-Silicon, is added, according to the product required. The pig-iron used at the Oberkampf Works, Paris, had the following composition :—

*Carbon,	3·50	Sulphur,	0·05
Silicon,	2·00	Phosphorus,	0·05
Manganese,	1·00		

When working the acid process, the converter is usually lined with best silica bricks, although there is no reason why it should not be rammed with ganister. Burnt fireclay twyers are generally used, tapered to permit of easy insertion and removal; in small 1-ton vessels, they are usually five in number. When the twyers are worn out, the wind-box is removed, the old twyers are cut away, ganister and fireclay are rammed in, a hole is pierced in this with a mandril the size of the twyer, and a new twyer inserted directly the clay has set hard. The converter has been used with a basic lining, and is said to have given good results, but very considerable trouble might be expected to arise in repairing the linings and in maintaining the twyers in good condition. The apparatus is one which is obviously more adapted for production of steel castings than for mild steel ingots, and there seems little reason for complicating matters by using basic linings, as small converters can never compete, as regards cost of production, with large vessels in the manufacture of mild steel. The waste in the Robert converter is said not to exceed 12 per cent. in acid work, and 13 to 18 per cent. in basic, and all one can say is that these results are very good, and far better than general experience with other small converters would lead one to anticipate. The following may be taken as typical analyses of soft Robert steel :—

	1.	2.
Carbon,	0·122	0·102
Silicon,	0·022	0·035
Sulphur,	0·048	0·032
Phosphorus,	0·052	0·049
Manganese,	0·411	0·307

The Walrand Legénisel Process.—This process is carried out in a small tipping converter, and is especially adapted for use for steel castings, as a hot very fluid metal is obtained which can readily be cast into any required form. The great difficulty in dealing with very small charges in Bessemer converters is to obtain the metal sufficiently hot, so that it can be readily dealt with in large or small quantities without skulling the ladles. Walrand obtains this result by introducing melted Ferro-Silicon after the Carbon has been practically removed, and then turning the vessel up again for a short *after-blow*, generally varying from 1¼ to 2 minutes. The heat generated by the combustion of the Silicon added, produces a very fluid metal, as all the heat is concentrated in the bath just when it is most needed, and, the Carbon having been previously removed, less heat is carried away in the escaping gases than if the Silicon pig had been added earlier in the blow, or if highly-silicious pig-iron had been charged at

* *Iron and Steel Inst. Journ.*, 1889, vol. ii., p. 272.

the commencement. Another objection to using a very silicious pig-iron is the great risk of leaving a very considerable percentage of Silicon in the finished steel (see p. 89), whereas by additions, and removal by an after-blow, the Silicon is reduced to a trace. The process is conducted as follows :— Pig-iron containing from 2·5 to 2·9 per cent. of Silicon is melted in a cupola, run into the converter, and the metal blown in the usual way to the drop of the flame, when a weighed quantity of Ferro-Silicon previously melted in a

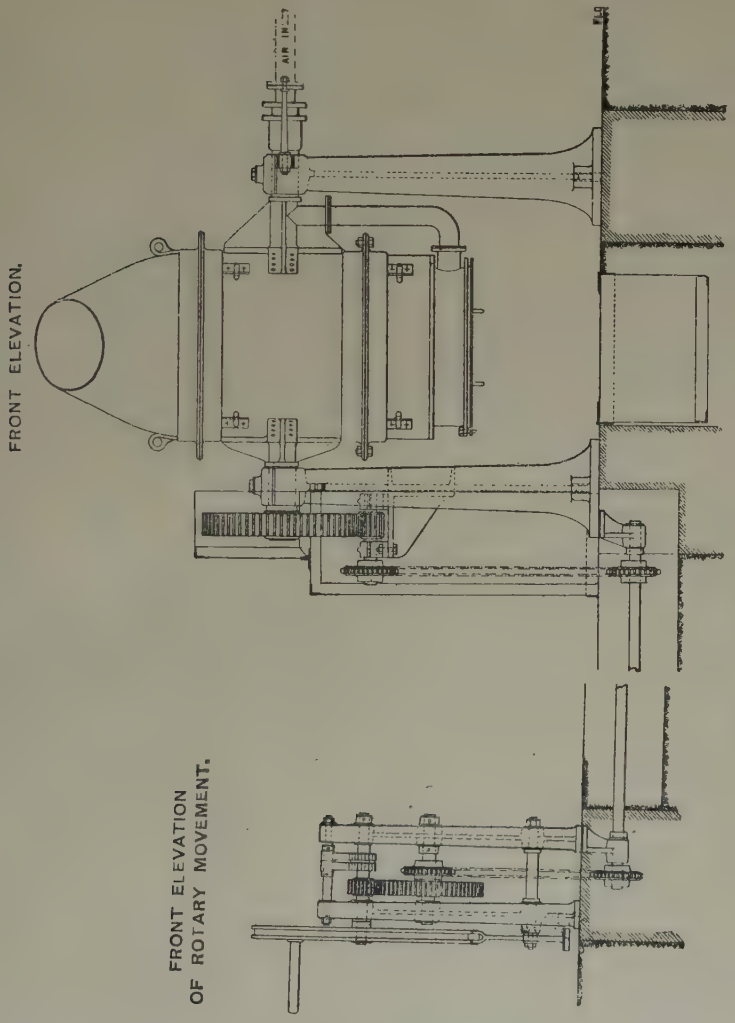


Fig. 75.—Walrand Legénisel Converter, showing hand rotating gear.

small cupola is added, and the blow continued until the whole of the Silicon is burnt out, which usually takes less than two minutes. Ferro-Manganese is then added, and the metal is ready for casting. The two vessels in use in Paris blow charges of 300 and 600 kilos. respectively, and are turned down by hand gearing, as shown in the sketch (fig. 75). There are six twyers in the small and eight in the large vessel. The metal is generally poured from the

converter into small hand ladles, and rapidly carried to the different moulds ready to receive it. From a small converter of similar construction some few years ago the author saw some extremely small castings, weighing only a few pounds, cast from practically Carbonless steel, and they were perfectly sound. The nose of the converter is usually covered up during the time of casting to retain the heat as much as possible.

The pressure of blast used varies from one to two atmospheres. Snelus* says the waste is about 10 to 12 per cent. in the converter, and about 15 to 17 including cupola waste, which is exceptionally low, considering the small charges. Practically any grade of steel from 0·08 of Carbon up to ·80 can be obtained, and the Silicon, &c., can be varied at pleasure by suitable additions. Whatever the grade of steel required may be, it is always obtained by completely decarburising first, and then recarburising with additions to the extent required.

Tropenas Process.—This, like the Walrand Legénisel and the Robert processes, aims at the production of small quantities of steel which shall possess great fluidity owing to the high temperature obtained during the process. The twyers are especially arranged to effect this, and also to eliminate the impurities by surface oxidation. The Tropenas converter in general form is similar to the ordinary side-blowing converter, but the bottom is somewhat conical, so that the bath of metal may present as large a surface as possible to the blast, and at the same time not be shallow. The air-blast instead of being injected into the molten metal is made to impinge upon its surface, the twyers being arranged above the metal line on one side of the converter. By having a deep bath, the metal is kept as still as possible, and not violently agitated as in other systems of blowing, when the blast is introduced at either the bottom or sides beneath the metal. This has the advantage of allowing a very low pressure of blast, 2 to 4 lbs. being employed, and according to Mr. Tropenas, a material very much freer from occluded gas is obtained, and in fact a metal equal in all respects to open hearth steel. The heat of the bath is greatly augmented by the combustion of the Carbon Monoxide formed from the oxidation of the Carbon in the metal by means of a subsidiary twyer above the slag line, through which air is injected. The form of converter and arrangement of the twyers are shown in figs. 76 and 77. The principal blast is introduced through the bottom row of twyers, which are known as the "twyers of reaction," and oxidation takes place on the surface only, air being admitted through the top twyers, or "twyers of combustion," when the Carbon commences to be oxidised. During the first period of the blow, the converter is kept in the position shown in fig. 76, no air being admitted through the top twyers; but as soon as the second period of the blow commences, as shown by the appearance of a flame at the mouth of the vessel, the valve of the top twyers is cautiously opened, air admitted, and the converter moved into position shown in fig. 77. The bottom twyers must be raised sufficiently above the level of the bath to prevent the slag chilling and closing the twyers, but some of the slag generally becomes cooled, and forms hollow projections which, although slightly closing the air inlets, do not seem to affect the operation appreciably; in fact, these slag nozzles protect the twyers which last about 30 to 40 blows.

The process is very similar to the Robert; both claim surface oxidation, and both that CO produced by oxidation of Carbon is burnt to CO_2 with corresponding increase of temperature of the bath, the only difference apparently being that the Robert converter is especially designed to give a

* *Iron and Steel Inst. Journ.*, 1894, vol. i., p. 34; 1896, vol. ii., p. 105.

rotatory motion to the metal, while the object of the somewhat deep conical bottom of the Tropenas converter is to keep the bath as free as possible from any mechanical disturbance. The combustion twyer above the reaction twyer is certainly a more effective way of insuring the combustion of the Carbon Monoxide than depending upon the injection of excess of blast by twyers at one level as in the Robert; but with this exception there would appear to be no great difference in the converters. The highly oxidising slag formed on the surface, combined with the circulation currents

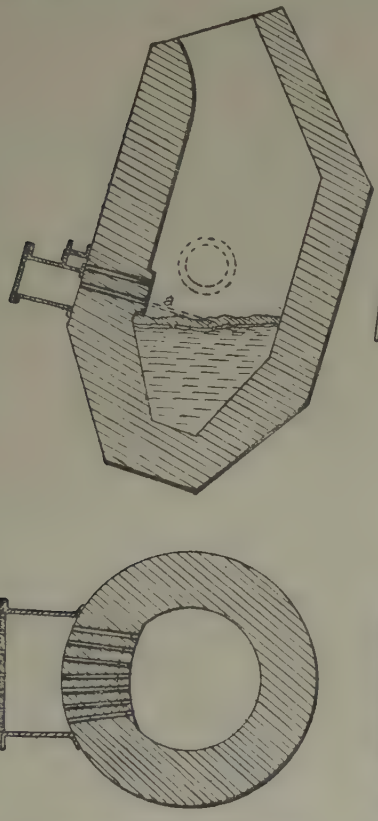


Fig. 76.—Tropenas Converter, showing position of Converter during early part of the blow when blast is entering only through twyers of reaction, a a.

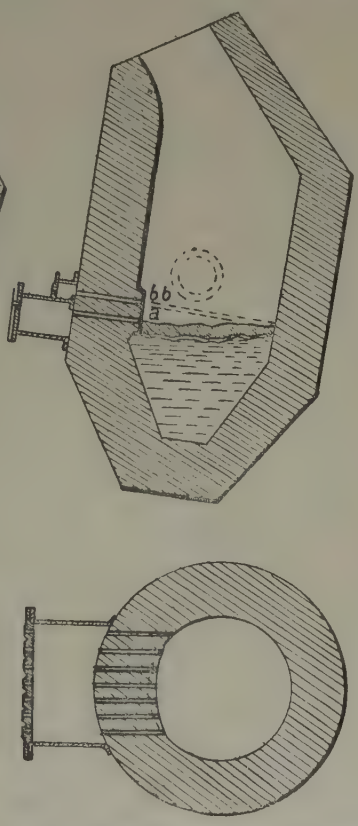


Fig. 77.—Showing position of Converter during the second period of the blow when air is admitted through bottom twyers, and also twyers of combustion, b.

set up in the metal bath, rapidly oxidise the impurities present. The inventor claims that the metal produced is equal in all respects to Siemens steel of the highest class, and the conditions in the converter are not dissimilar to those of an open hearth furnace, as there is a comparatively large surface of metal exposed to a very oxidising slag. The slag is probably far more oxidising, especially towards the end of the blow, than in an ordinary open hearth furnace, and the rapidity of the oxidation of impurities is undoubtedly assisted by the circulation of the metal induced by the injected air currents. It might be expected that these conditions would

greatly increase the liability to produce over-oxidised metal as compared with the open hearth process, especially as it seems the custom to decarburise completely, and to produce the required grade of steel by addition of Ferro-Manganese, Spiegel, Ferro-Silicon, &c. Converters to blow only 10 cwts. of metal can be used successfully, and generally speaking the process lends itself to the production of small castings. With a 2-ton converter large castings can, however, be made, as it is possible to keep the metal from one charge in the ladle while another charge is being blown, and in this way with two 2-ton converters, castings up to 10 tons can be made, or with a single 2-ton converter, 3 to 4 tons casting can be produced. The waste is said not to exceed 14 per cent., which is exceptionally little for such small heats, and is certainly surprising considering the large amount of surface oxidation. The process can be worked either as an acid or a basic one, but there would appear to be little advantage in using the latter, and many difficulties would arise in regard to linings and in dealing with the slag. The process is at work at Woolwich Arsenal, where there are three converters which are said to give extremely satisfactory results.

The Stock Converter.—This is a combination of an oil-melting furnace and small side-blown converter which has lately been erected at the Darlington Forge, and is said to be giving very good results. Materials are charged cold into the previously-heated converter; oil fuel under a pressure of about 40 lbs. to the square inch is supplied through flexible tubing to small tubes about $\frac{1}{12}$ of an inch in diameter, let into the main blast twyers, which are about 2 inches in diameter, and air for combustion, at a pressure of about $1\frac{1}{2}$ lbs., is admitted. When the charge is melted, which takes about $1\frac{1}{2}$ hours for a 3-ton charge, the converter is rotated to the blowing position, the oil shut off, and the bath of metal subjected to a blast of air on the surface for about 16 to 19 minutes, when the vessel is rotated into the teeming position and finishing metal added in the usual way. The waste gases pass through an economiser which, when the converter is in the blowing position, is opposite the mouth of the converter, and this economiser contains the blast pipes through which the blast passes on its way to the converter, and in passing through which, it is heated up to a temperature of about 800° F. Owing to the intense heat developed during melting and blowing with heated blast, the converter has to be lined with magnesite bricks, but low phosphoric iron is used and no attempt is made to dephosphorise. The advantages of this converter are that no impurities are taken up by the pig-iron during melting, as in case of coke melting in cupolas, and owing to the hot blast being used a very high temperature is obtained, insuring a very fluid metal, which makes the process particularly applicable for manufacture of steel castings. The vessel is mounted so that it can be rotated into the different positions for charging, blowing, and teeming.

Small Converters Considered generally.—Although these small converters still have some enthusiastic supporters, with the few exceptions where manufacturers find it necessary to make their steel in comparatively small quantities under their own supervision, these converters are used almost exclusively for steel castings, and even under such circumstances the general consensus of opinion seems to be that a small open hearth plant gives better all-round results. For castings, especially where small ones have to be made, and metal has to be kept extremely hot and fluid, these small tipping converters undoubtedly offer certain advantages over a Siemens furnace. Steel can be made in smaller quantities, the converter can be used as a ladle to distribute the steel in small ladles for different castings, and thus the metal be kept very hot until the whole heat has been cast. Frequent charges can be made during the day, instead of one charge as in the

open hearth furnace. Less space is required in the moulding shop, for as soon as one set of castings is set, they can be removed and moulding recommenced, whereas for a Siemens furnace sufficient moulding space must be available to take an entire charge, probably of not less than 5 or 6 tons. At all events, whatever may be the future of small converter plants, it is in the direction of steel founding that they are most likely to develop, as they cannot hold their own against the large outputs of Siemens or Bessemer plants for ordinary steel manufacture, and are also handicapped by the large waste which occurs during conversion.

CHAPTER IV.

CHEMISTRY OF THE ACID BESSEMER PROCESS.

General Considerations.—The reactions taking place in the acid-lined Bessemer converter, under various working conditions, have been carefully studied by Snelus in this country, by Kupelwiesser and Ledebur on the Continent, and by F. Julian in America, while the thermo-chemistry of the subject has received special attention from Jordan, Akerman, Pourcel, and, later, from Professor Hartley.

To arrive at the chemical history of the Bessemer blow it is necessary to examine the bath of metal at repeated intervals, and note the changes produced; also to examine the products of oxidation, and to consider the thermal conditions existing at each period when samples are taken. The products of combustion are either gaseous or liquid, the former passing away with the Nitrogen at the mouth of the converter, and the latter fusing at the intense heat developed to form a more or less fluid slag, which, being lighter than the molten metal, floats upon its surface.

Three Stages Involved.—The reactions taking place in the acid Bessemer blow are usually divided into three stages or periods—1st, the slag-forming period; 2nd, the boil; and 3rd, the finishing period. During the first period the greater portion of the Manganese and Silicon are oxidised, and unite with some Oxide of Iron simultaneously produced to form a double Silicate of Iron and Manganese slag; and under normal conditions of working the Carbon is not appreciably attacked until a considerable portion of the Silicon has been removed, such proportions as are oxidised passing away mostly as Carbon Dioxide (CO_2). This period is marked by an irregular violet-coloured flame at the mouth of the converter, which gradually becomes more steady in character and changes to a yellow colour as the temperature of the bath increases. After about five or six minutes from the commencement of the blow, the Carbon begins to oxidise rapidly, and, the bath being very fluid owing to the high temperature produced by the combustion of a relatively large proportion of Silicon, the second period, known as the boil, commences. During this period the oxidation of the Silicon and Manganese continues, and the greater part of the Carbon is also removed, mostly in the form of Carbon Monoxide (CO), as the percentage of CO_2 formed in the early part of the blow rapidly decreases, while the CO increases, as will be seen from the curves in fig. 79. It is the formation and escape of this gas which causes the violent agitation of the bath, and is attended with a very large flame issuing from the mouth of the converter, and with the ejection of considerable quantities of metal and slag, and a further increase in the temperature, and consequently in the fluidity of the metal. Some Hydrogen is found in the gases issuing from mouth of converter during this part of the blow, derived from the dissociation of water vapour in the blast.

During the last period the small amount of Silicon left and the remainder of the Carbon are oxidised, the latter to Carbon Monoxide, the temperature being too high to admit of the production of Carbon Dioxide in the presence of iron. Some iron is also oxidised, as will be seen from the analyses of slag in Tables viii. and xii., where it will be noticed that the oxide rapidly increases between the end of the boil and the addition of Spiegel; although in cases where low Silicon pig-iron is used, and consequently a comparatively low temperature prevails, as in American practice, this is not very marked, and is in fact hardly perceptible at times. At the end of the boil the flame at the mouth of the converter rapidly contracts, and the final disappearance

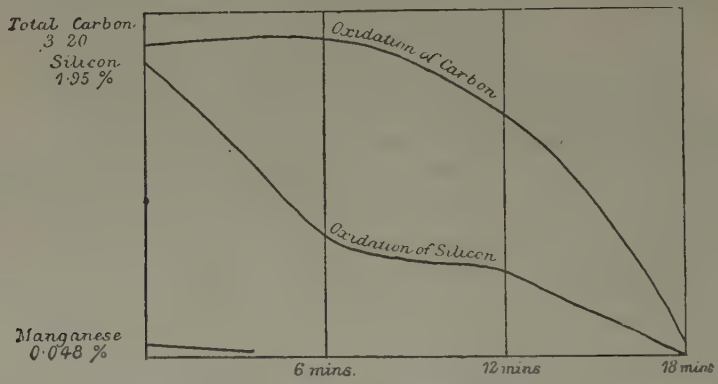


Fig. 78.—Curves showing removal of Carbon, Silicon, and Manganese in Acid Bessemer Process. (From analysis by Snelus.)

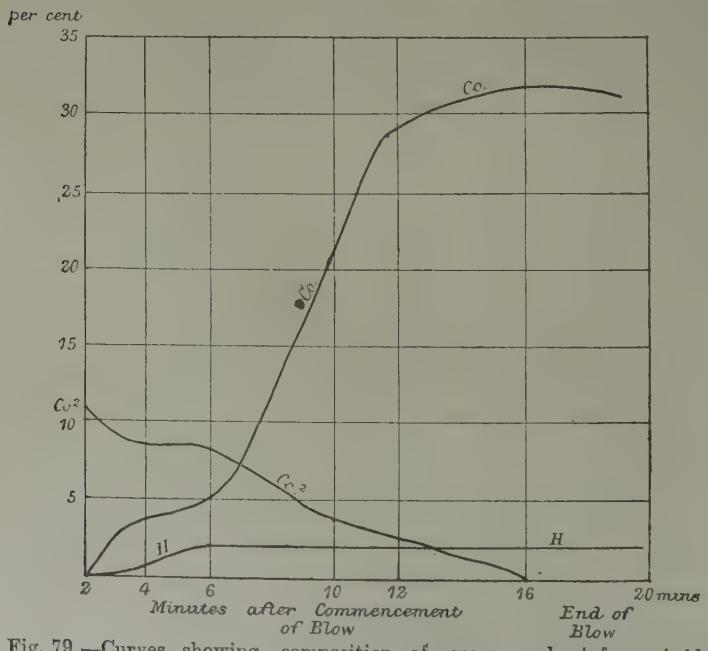


Fig. 79.—Curves showing composition of gases evolved from Acid Bessemer Converter at different stages of the Blow.

of the Carbon is marked by the "drop of the flame," which indicates that the conversion is complete; the blast is then shut off, and the vessel immediately turned down.

The following analyses of gases, and curves deduced therefrom, illustrate the reactions taking place during the blow :—

TABLE VII.—Analyses by Snelus of Gases from Bessemer Converter.

	Minutes from commencement of operation.					
	2	4	6	10	12	14
Carbon Dioxide, . .	10·71	8·59	8·20	3·58	2·30	1·34
Oxygen, . . .	0·92	...	0	0	0	0
Carbon Monoxide, .	0	3·96	4·52	19·59	29·30	31·11
Hydrogen, . . .	88·37*	0·88	2·00	2·00	2·16	2·00
Nitrogen, . . .		86·57	85·28	74·83	66·24	65·55
Carburets of Hydrogen,	...	...	...	...	0	...
	100·00	100·00	100·00	100·00	100·00	100·00

A certain amount of both iron and Manganese is volatised during the second and final stages of the blow, but especially during the latter, when the metallic vapours are carried out into the air where with the Carbon Monoxide they are burnt.

Production of Fume.—The following analysis of fume is by Schöffel, and Prof. Hartley † considers that its composition suggests the volatilisation of Silica, or some Silicate or Silicon :—

FeO, 16·29; MnO, 48·23; SiO_2, 34·86.

The percentage of iron in the fume increases towards the end of the blow, since, for the complete removal of metalloids, a certain amount of over-blowing or oxidation of the iron is necessary; and it seems probable that some of this oxide produced is carried away by the blast mechanically, rather than that the large proportion found in the fume has been volatilised. If blowing is continued so that the brown fumes become extremely dense, there is no corresponding increase in temperature to account for increased volatilisation. That Manganese is comparatively volatile has been distinctly proved, and there seems considerable probability that this element is volatilised to a small extent.

The Carbon, although responsible for the development of a certain amount of heat, plays a comparatively unimportant part in this respect, owing to the greater amount of the Carbon being oxidised only to CO—or, if oxidised to CO_2, being again reduced to CO—and also to the fact that all the products of its combustion, being gaseous, escape with the air, carrying away a considerable amount of heat. Silicon is the great heat producer; it plays an important part in rapidly forming a slag, and a certain amount of this element is necessary in all pig iron required for the Bessemer process. Manganese, within certain limits, is a very useful constituent, especially when the Silicon is low, as it raises the temperature of the bath, forms a fluid slag, protects the metal from

* Hydrogen not determined separately.

† "Cantor Lecture," March, 1898, by Prof. Hartley.

over-oxidation, and, lastly, tends to remove the Sulphur from the molten metal. Sulphur and Phosphorus are not oxidised, or, if oxidised, are immediately reduced again in the presence of a siliceous slag, and pass back into the metal. During the Bessemer blow of a 10-ton charge of metal having the following composition—Carbon, 3·50; Silicon, 2·00; Manganese, 1·00—7 cwts. of Carbon, 4 cwts. of Silicon, and 2 cwts. of Manganese are burnt, and as Silicon is a much greater heat producer than Carbon the intense temperature developed in the Bessemer converter is readily accounted for.

Mass Action in the Converter.—The influence of mass on chemical action has a most important bearing on the reactions which take place in the Bessemer converter. It cannot be supposed that traces of impurities are seized by the Oxygen out of the large mass of metal and oxidised directly, but it is generally admitted that the oxidation is an indirect reaction, Magnetic Oxide being first formed near the twyers, and reduced by the impurities in the bath to FeO and Fe as it passes upwards. The Oxide formed at the twyers thus acts as a carrier of Oxygen to the impurities in the bath, and the oxidation and reduction of iron goes on until all impurities are practically removed, when, if the blow is not at once stopped, the bath of metal rapidly becomes "burnt"—*i.e.*, surcharged with Oxide of Iron.

Thus the great affinity of Carbon, Silicon, and Manganese for Oxygen enables them to act as reducing agents to the Oxide of Iron formed, and, while being themselves oxidised and removed, they prevent, as long as they are present in the bath, any over-oxidation of the iron.

Silicon being the most readily oxidisable element in the metal, its reducing action is so great that, until it has been largely removed, the oxidation of the Carbon does not, under ordinary conditions of temperature, commence, as will be seen from the curves and analyses on pp. 87, 88, *et seq.* So great is the affinity of Silicon for Oxygen, that it is capable of decomposing to a large extent any Carbon Monoxide produced, giving rise to the formation of Carbide of Iron, and so preventing the oxidation of the Carbon during the early stages of the blow.

The Function of the Slag.—The action of the slag in the Bessemer converter is a somewhat disputed question—Akerman holding strongly the view that it plays a most important part in the oxidation of the impurities, as it does in other refinery processes. This view, he considers, is supported by the changes in the slag during the operation, as in nearly all cases the percentage of Ferrous Oxide is considerably reduced during the boil, showing that it must have acted as an oxidising agent to the impurities in the metal. As, however, was pointed out by Campbell,* in discussing this point, the amount of available Oxygen calculated on the weight of the Ferrous Oxide present is too small to have very much influence, unless we assume that it acts as a carrier of Oxygen to the bath. That the slag has some oxidising effect, there can be little doubt, as in the Basic Bessemer process it is possible to add from 10 to 15 cwts. of Oxide of Iron to a 7-ton charge without appreciably increasing the percentage of iron in the finished slag; but it is certain that the slag does not play anything like the important part it does in the Siemens furnace. In the latter all the Oxygen of the air has to pass through the slag first, when once the bath is melted, before it reaches the metal, whereas, in the Bessemer process, the Oxygen has to pass through the metal before it reaches the slag. The probability is that when a very oxidising slag is formed in the early part of the blow during the boil, the metal and slag being more or less intimately mixed, the latter gives up part of its Oxygen until a state of approximate equilibrium is established,

* *Trans. American Inst. Mining Engineers*, vol. xxii., pp. 668-9.

That is to say, for a particular set of conditions depending upon the composition of the slag, the composition of the metal bath, the temperature of the metal, &c., &c., the slag is capable of retaining only a certain amount of Oxide, and Oxide of Iron will pass into or be reduced from the slag, as the conditions vary during the blow.

Composition of Pig-iron.—The pig-iron used for acid Bessemer steel manufacture may vary within very considerable limits—

1. Low Silicon (under 1·0 per cent.) and high Manganese (from 2·4 per cent.), as in most Swedish works.
2. Low Silicon (under 1·00 per cent.) and low Manganese (under 0·5 per cent.), as in many American works.
3. High Silicon (from 2 to 2·5 per cent.) and low Manganese (·75 per cent. and less), as in most English works.
4. Occasionally high Silicon (2 per cent. and over) and high Manganese (2 per cent.).

Under suitable conditions good steel can be made from all these classes of iron, but whatever the percentage of Silicon or Manganese, the Phosphorus and Sulphur must both be below ·06 per cent., as neither of these constituents is removed during the blow.

Low Silicon and High Manganese Pig-Iron.—The use of this class of iron is almost exclusively confined to Sweden, as the native ores containing Manganese produce a pig-iron which is low in Silicon, often contains 3·5 to 4·5 per cent. of Manganese, and is exceptionally free from Sulphur and Phosphorus. To the low Silicon and high Manganese is largely due the fine quality of the finished product, as they jointly develop just enough heat to enable the metal to be cast. The Manganese also plays an important part in preventing oxidation of the metallic bath, for even if blown quite down, the Manganese is rarely completely removed, as will be seen from the analyses and curves given. The practice in Sweden is not to blow until the Carbon is completely removed, and then to recarburise by additions of Ferro-Manganese, Spiegel, &c., but to stop the blow at the point when the required degree of decarburisation has been reached. The Manganese in the pig-iron not only protects the bath of metal from direct oxidation, but has a distinct tendency to remove Sulphur from the metal, and has the most important indirect effect of producing a very fluid slag which is at the same time far less oxidising than a rich iron slag. Akerman* is of opinion that the great fluidity of the slag in Swedish Bessemer practice plays a most important part in removing Oxide of Iron from the metal, as the more liquid the slag, the more completely it is brought into intimate contact with the metal, and the more readily does it remove and absorb Oxide of Iron, which would otherwise remain in the bath of metal. On the other hand, Manganese rapidly attacks the lining of the converters, and increases the waste. The Carbon is generally somewhat higher in these Manganiferous irons than in ordinary hematites, but this is no disadvantage, except that it slightly increases the waste, and prolongs the operation. The large amount of Carbon and Manganese present supplements the heat given out by the Silicon, and without the high percentage of these elements it would probably be impossible, considering the small charges worked, to cast the metal satisfactorily, as conditions do not lend themselves to the rapid work which is so essential a feature of American practice when working low Silicon pig. The following are analyses of samples taken with slags corresponding, during a Swedish Bessemer blow, and figs. 80 and 81 show graphically the rate of removal of impurities :—

* *Trans. American Inst. Mining Engineers*, vol. xxii., p. 282.

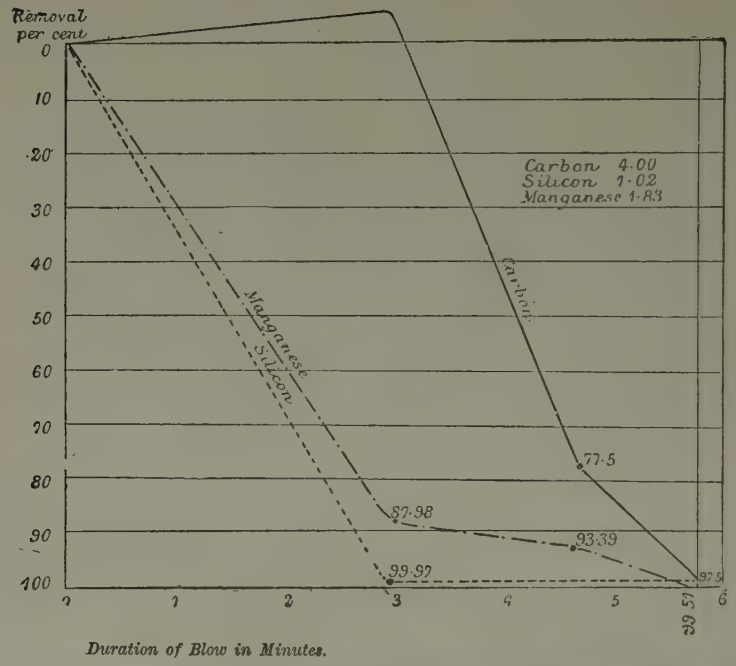


Fig. 80.—Elimination of Carbon, Silicon, and Manganese, Acid Bessemer; Low Silicon, Medium Manganese, Swedish practice. In this case not only is there no decrease in Carbon during first 3½ minutes, but a *relative* increase.

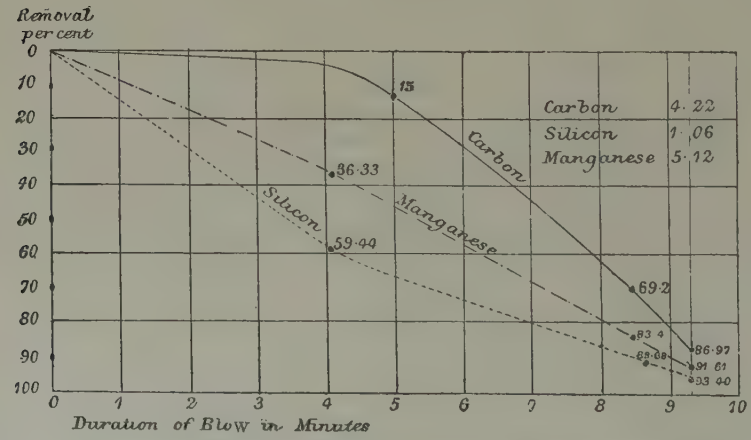


Fig. 81.—Elimination of Carbon, Silicon, and Manganese, Acid Bessemer. Swedish practice, Low Silicon, very High Manganese.

TABLE VIII.

	No. 1. Medium Manganese.				No. 2. Very High Manganese.			
	Furnace Metal.	3 m.	4 m. 45 s.	5 m. 45 s.	Furnace Metal.	4 m. 15 s.	8 m. 35 s.	9 m. 20 s.
Carbon,	4·00	4·30	·90	·10	4·22	4·20	1·30	·55
Silicon,	1·02	·03	·03	·03	1·06	·43	·12	·07
Manganese,	1·83	·22	·12	·09	5·12	3·26	·85	·43
				Slag.				
Oxide of Iron,	...	14·20	18·52	31·19	...	4·20	6·24	9·45
Oxide of Manganese,	...	26·31	31·01	25·43	...	46·38	52·26	48·92
Magnesia,	...	·22	·14	·11	...	·54	·29	·46
Lime,	...	·62	·38	·32	...	1·26	·70	1·00
Alumina,	...	2·86	2·70	2·24	...	3·08	2·49	2·94
Silica,	...	55·26	47·20	40·5 0	...	45·87	39·07	37·63

In blowing metal with 2·5 per cent. and upwards of Manganese, sufficient is usually left in the bath at the end of the blow to make further addition of this metal quite unnecessary; and many thousands of tons of steel have been made in Sweden without either any Ferro-Manganese or other finishing metal being added, the finished product being entirely free from red shortness. Probably the low percentage of Sulphur in the pig-iron used largely enables these excellent results to be obtained, and it is more than doubtful if, with Sulphur equal to that in ordinary English hematite, the same freedom from red shortness could be insured without Manganese additions.

The percentage of Sulphur originally present in Swedish pig-iron is so low that the influence of Manganese in further reducing this is not easily noticed; but both in acid and in basic practice, whether Bessemer or Open Hearth, a Manganiferous slag always tends to reduce the Sulphur in the finished metal.

TABLE IX.—Analyses of Gases by M. Tamm from Two Blows at Westanfors Works, Sweden.

First Series.	Minutes from Commencement of Operation.			
	3 to 4.	9 to 10.	21 to 24.	26 to 27.
Carbon Dioxide,	9·127	5·998	4·856	1 853
Oxygen,	4·762	1·699	0·967	0·550
Carbon Monoxide,	0	17·555	19·322	14·311
Hydrogen,	0	0·908	1·120	1·699
Nitrogen,	86·111	78·840	73·735	81·587
Second Series.	**2 to 3.**	**8 to 10.**	**12 to 15.**	**17 to 19.**
Carbon Dioxide,	6·608	6·608	4·144	2·995
Oxygen,	7·256	1·206	0·989	1·318
Carbon Monoxide,	0	15·570	25·580	25·606
Hydrogen,	0	1·112	1·040	1·120
Nitrogen,	86·136	76·400	68·256	62·061

The foregoing table gives the analyses of gases taken at different periods during a Swedish blow; and it will be seen that free Oxygen is present during the entire operation, although gradually decreasing towards the end of the blow. This differs from the results obtained by Snelus, as will be seen by referring to the table on p. 81, he finding no free Oxygen after the first few minutes. This difference in the composition of the gases may have been due to the depth of metal blown being very small compared to the pressure of the blast. In other respects, the analyses confirm results obtained under dissimilar conditions, Carbon Monoxide increasing, and the Carbon Dioxide decreasing as the blow proceeds, the percentage of Hydrogen depending upon the amount of water vapour in the air.

Low Silicon and Low Manganese Pig-Iron.—That the temperature of the Bessemer charge principally depends upon the Silicon in the pig-iron, was first pointed out by Prof. Jordan,* of the Ecole Centrale in Paris, in 1869, and then by Prof. R. Akerman in 1872;† and for many years the pig-iron for Bessemer work has been selected by its content of Silicon, either high or low, to meet the special conditions of work, whether a hot or cold metal is required. The larger the quantity of metal blown, and the greater the rapidity with which the blows follow one after the other, the less Silicon will be required to keep up the heat of the bath; consistent with maintaining the metal fluid, the lower the Silicon the better, as there will be less waste, and quite as good, if not a better product.

In America, the practice in many works is to use metal very low in Silicon, from ·8 to 1·2, which enables very rapid work to be done, the entire blow not lasting more than eight or nine minutes; the heat developed by such pig-iron is barely sufficient to keep the steel fluid for casting, and it is only by most rapid working—one heat following another practically without any interval, so that converters, ladles, &c., &c., are all kept extremely hot—that it is possible to avoid "skulling" in the ladle.

The advantages of low Silicon are:—(1) That a better yield is obtained, due, not only to the smaller amount of Silicon actually removed, but also to the smaller quantity of iron fluxed away in the form of Ferrous Silicate, as, especially in the absence of Manganese, iron is the most readily available base, and combines with the Silica to form a Silicate with consequent loss of metal.

(2) The larger the amount of Silicon in the metal, the larger obviously will be the amount of Oxygen required, and, consequently, the duration of the blow will be longer, and the wear and tear on the converter lining, especially on the bottoms, will be greater. On the other hand, with metal very low in Silicon, there is always considerable risk of not developing sufficient heat, and of the metal setting either in the converter or in the ladle. The general effect of Manganese in the Bessemer converter has already been referred to in the last paragraph, and its absence means that considerable additions of either Ferro or Spiegeleisen must be made at the end of the blow to remove all traces of red shortness caused by over-blowing. Indirectly, Manganese is a very important factor in Bessemer work, especially when low Silicon pig is used, as low Manganese and low Silicon in the pig generally indicate high Sulphur, and high Sulphur means red shortness in the finished product. In this country, at all events, it has not been found possible to produce regularly, on a commercial scale, pig-iron with 1 per cent. of Silicon or less, 0·5 per cent. of Manganese, and under 0·10 per cent. of Sulphur, although in America a pig-iron low both in Silicon and in Sulphur is made regularly in

* *Bulletin de la Société des Ingénieurs Civils.*
† *Iron and Steel Inst. Journ.*, 1872, vol. ii.

certain districts—a result probably due largely to a very low Sulphur coke being available.

TABLE X.—American Practice.

	Initial Charge.			Time of Actual Blowing.						
	Molten Metal.	Steel Scrap estimated.	Aver'ge Composition of Charge.	2 Min.	M. S. 3.20	M. S. 6.3	M. S. 8.6	M. S. 9.10	Speigeleisen Added.	After Adding Speigeleisen.
Carbon,	3·10	0·36	2·98	2·94	2·71	1·72	0·53	0·04	4·64	0·45
Silicon,	0·98	0·08	0·94	0·63	0·33	0·03	0·03	0·02	0·035	0·038
Manganese,	0·40	0·97	0·43	0·09	0·04	0·03	0·01	0·01	14·90	1·15
Phosphorus,	0·101	0·10	...	0·104	0·106	0·106	0·107	0·108	0·139	0·109
Sulphur,	0·06	0·08	0·06	0·06	0·06	0·06	0·06	0·06	...	0·059
Slag.										
Silica,	...	...	...	42·20	50·26	62·54	63·56	...	...	62·20
Alumina,	...	...	...	5·63	5·13	4·06	3·01	...	...	2·76
Ferrous Oxide,	...	...	...	40·29	34·24	21·26	21·39	...	...	17·44
Ferric Oxide,	...	...	...	4·31	0·96	1·93	2·63	...	...	2·90
Mangan. Oxide,	...	...	...	6·54	7·90	8·79	8·88	...	...	13·72
Lime,	...	...	...	1·22	0·91	0·88	0·90	...	...	·87
Magnesia,	...	...	...	0·36	0·34	0·34	0·36	...	...	·29
Phosphorus,	...	...	...	0·008	0·008	0·010	0·014	...	...	·010
Sulphur,	...	...	...	0·009	0·009	0·014	0·008	...	...	·011
Appearance of flame,	...	...	...	Silicon flame.	Brightening.	Moderate Carbon flame.	Full Carbon flame.	Flame drops.	Blown 10 secs. after drop.	...
Cubic feet of air,	...	...	...	34,502	30,628	53,481	45,365	26,430	1,868	...
Cubic feet of air per minute,	...	...	...	17,251	22,971	19,691	21,810	25,685	11,208	...

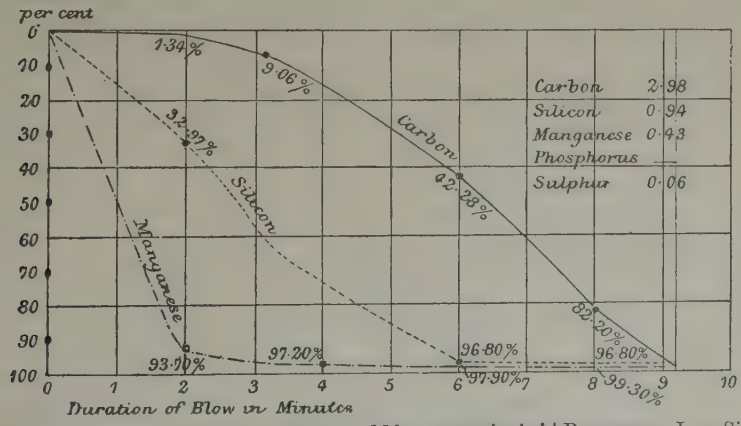


Fig. 82.—Elimination of Carbon, Silicon, and Manganese in Acid Bessemer. Low Silicon, and Low Manganese (American Practice).

In Table x. are given the analyses of a series of samples of metal and slag * taken during a low Silicon blow, and fig. 82 expresses graphically the rate of removal of the impurities. It will be noticed that neither Phosphorus nor Sulphur decreases; in fact there is a slight increase, and that the slag, after the addition of Spiegel, contains less Oxide of Iron and more Oxide of Manganese, which seems to point to the conclusion that some iron has been reduced from the slag by the Manganese of the Spiegel.

The increase of both Sulphur and Phosphorus is generally somewhat greater than that shown by these analyses, and it may generally be taken that such increase will be directly proportional to the waste or loss during blowing, and that these impurities will be concentrated in the steel to the extent of such loss.

High Silicon and Low Manganese Pig-Iron.—Pig-iron with about 2 per cent. of Silicon may be considered to represent fairly the iron used, and is found to give the best results, in English and Continental Bessemer practice. Pig-iron of this composition can be regularly and easily made low in Sulphur, and the heat developed is sufficient to avoid any risk of serious skulling. English plants are not adapted for the very rapid work customary in America, and consequently the metal used must be capable of developing more heat to allow for the loss by radiation from the vessels, &c., &c. Sometimes the Silicon is as high as 2·5 to 3·00 per cent., but if so, it is generally necessary to cool the blow by scrapping, and 2·0 to 2·25 per cent. of Silicon is what is preferred. The Manganese rarely exceeds 0·75 per cent., and Sulphur and Phosphorus should not be above ·05 per cent., and frequently are as low as ·035 per cent. Below are given analyses (Table xi.), by Snelus, of samples of metal taken from a Bessemer blow, and the curves (fig. 83) are deduced from these, and may be taken as fairly representative of the English practice, except that the Manganese in the pig-iron is exceptionally low. Temperature has a very marked influence on the removal of impurities, and as this temperature depends principally upon the Silicon present, the question of Silicon is very important. Provided the metal can be obtained hot enough to cast readily into ingot moulds, and free from Sulphur, the lower the Silicon in the pig-iron the better, as not only is the yield better, but the ingots will probably be sounder; if the Silicon is very high, there is considerable risk of its not being completely removed. Under ordinary conditions, the Silicon is oxidised from the commencement, and passes out rapidly at first before the Carbon is largely attacked, and then more gradually with the Carbon during the remainder of the blow, being almost completely removed before

TABLE XI.—English Practice—Analyses at the Dowlais Works.

	Molten Metal.	Time of Blowing.			After addition of Spiegel.
		6 min.	9 min.	13 min.	
Graphite, - - -	2·09	–	...	...	...
Combined Carbon, -	1·20	2·127	1·55	0·097	0·566
Silicon, - - -	1·952	0·795	0·635	0·020	0·030
Sulphur, - - -	0·014	Trace.	...	Trace.	...
Phosphorus, - -	0·048	0·051	0·064	0·067	0·055
Manganese, - - -	0·086	Trace.	...	Trace.	0·309
Copper, - - -	...	...	...	...	0·039

* Howe, *Iron and Steel Inst. Journ.*, 1890, vol. ii., p. 102.

the drop of the flame. If, however, from any cause—either a very high percentage of Silicon or a very high initial temperature of the metal—the temperature of the bath exceeds a certain point, the Carbon is attacked in preference to the Silicon, with the result that the Carbon is removed before the Silicon. This was pointed out by Snelus as long ago as 1871, when he gave various instances of a considerable percentage of Silicon being found

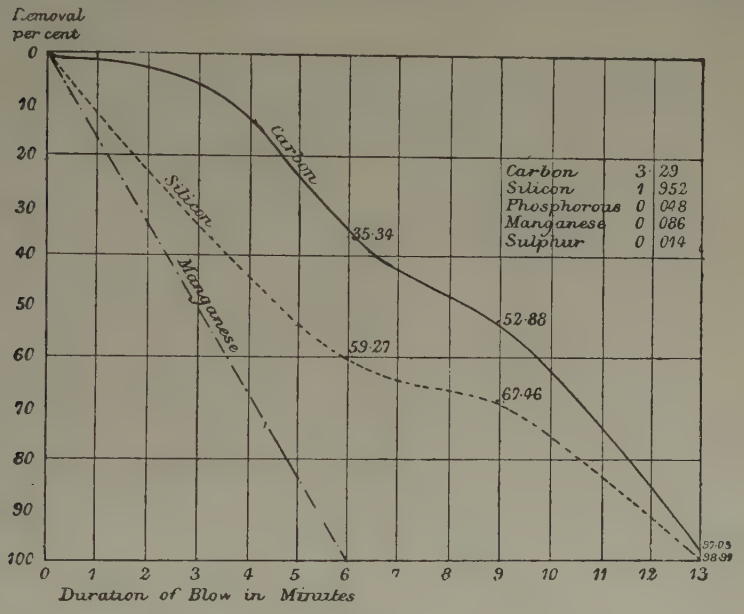


Fig. 83.

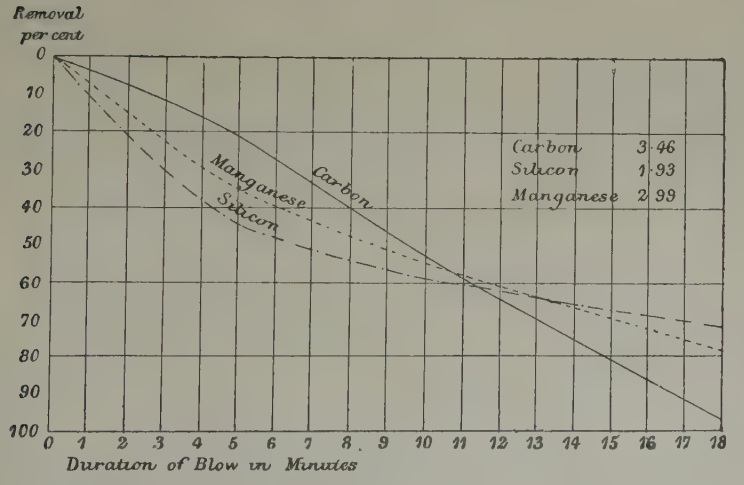


Fig. 84.—Elimination of Carbon, Silicon, and Manganese in Acid Bessemer, with fairly high Silicon, and high Manganese pig, showing practically complete removal of Carbon before Silicon and Manganese.

in finished *low* Carbon steel. One case came under the author's notice some years ago, in which a low Carbon steel with about ·12 per cent. Carbon contained 0·90 per cent. of Silicon. According to Mr. Campbell, it was the practice in Germany at some works to make high Silicon steel for special purposes by blowing a silicious pig. This removal of Carbon before the Silicon is shown in diagram (fig. 84).

High Silicon and High Manganese Pig-Iron.—Pig-iron of this composition is not often employed, at all events in England, as such iron is not produced commercially in any large quantity; but below (Table xii.) are given analyses of samples by Kessler and Muller, and the curve (fig. 85), and Tables xiii. and xiv. give particulars of other similar charges. The high temperature developed by the Silicon would produce a very fluid slag of Silicate of Manganese, which would in all probability be very destructive to the linings of the converters.

TABLE XII.—KESSLER AND MULLER'S RESULTS.

	Pig Metal.	Converter Samples.—Times of Blowing.			
		1 5 min.	2 10 min.	3 15 min. End of Blow.	4 After Addition of Spiegel.
Carbon, graphitic,	3·180	...	...	...	...
,, combined,	0·750	2·465	0·949	0·087	0·234
Silicon,	1·960	0·443	0·112	0·028	0·033
Phosphorus,	0·040	0·040	0·045	0·045	0·044
Sulphur,	0·018	Trace.	Trace.	Trace.	Trace.
Manganese,	3·460	1·645	0·429	0·113	0·139
Copper,	0·085	0·091	0·095	0·120	0·105
Corresponding Slags from Converter.					
Silica,		46·78	51·75	46·75	47·27
Alumina,		4·65	2·98	2·80	3·45
Ferrous Oxide,		6·78	5·58	16·86	15·43
Manganese Protoxide,		37·00	37·90	32·23	31·89
Lime,		2·98	1·76	1·19	1·23
Magnesia,		1·53	0·45	0·52	0·61
Alkalies,		Traces.	Traces.	Traces.	Traces.
Sulphur,		0·04	Traces.	Trace.	...
Phosphorus,		0·03	0·02	0·01	0·01

TABLE XIII.*

	Initial Charge.	Time of Actual Blowing—Minutes.				After the Addition of Spiegeleisen.
		5	10	15	20	
Carbon,	3·03	3·17	3·19	1·61	0·19	0·21
Silicon,	2·41	1·26	0·27	0·03	0·01	0·16
Manganese,	2·45	0·70	0·19	0·12	0·06	0·22

* *Dingler's Polyt. Journ.*, Band ccv., p. 456.

TABLE XIV.

	Initial Charge.	Time of Actual Blowing—Minutes.			After Addition of Spiegeleisen.
		5	10	18	
Carbon, - -	3·460	2·710	1·630	0·092	0·104
Silicon, - -	1·930	1·070	0·790	0·532	0·346
Manganese, -	2·990	1·920	1·368	0·538	0·621

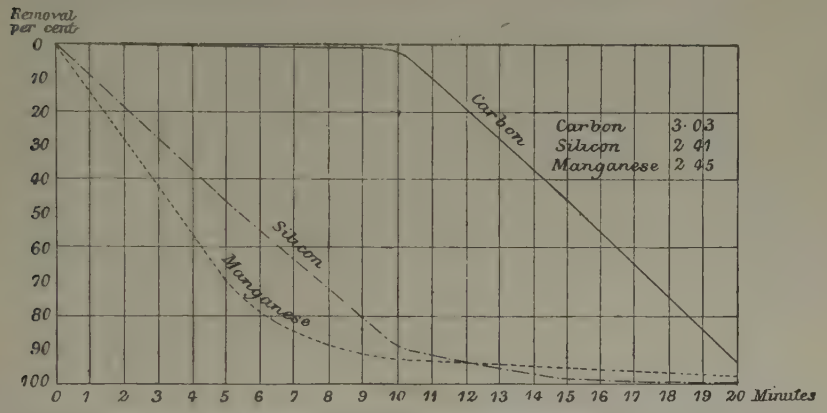


Fig. 85.—Elimination of Carbon, Silicon, and Manganese in Acid Bessemer. High Silicon and High Manganese. (Kessler.)

In carefully examining the various diagrams, it will be noticed that although the removal of the impurities is similar in many cases, yet the composition of the metal and conditions of working have very considerable effect on such removal, the Carbon being attacked much earlier in the blow, in some cases, than in others. Such differences may be due in part to errors arising from the difficulty of obtaining representative samples of the bath of metal during the different periods of the blow, and consequently the results must not be regarded as in any sense absolute, but simply as giving a general indication of the oxidising reactions which take place in the converter under a certain set of conditions.

CHAPTER V.

THE CHEMISTRY OF THE BASIC BESSEMER PROCESS.

Acid and Basic Process Contrasted.—The removal of the Carbon, Silicon, and Manganese in the basic Bessemer process, is exactly the same as in the acid Bessemer, except that the removal of the Silicon is more complete. The real difference between the processes commences after the removal of the Carbon, at the drop of the flame, as, on continuing the blowing, the Phosphorus is attacked, and combines with the lime in the slag to form a stable Phosphate of Lime. This continuation of the blow after the removal of the Carbon is known as the "after blow," and before this stage is reached the Phosphorus is removed to a very slight extent only. The elimination of Phosphorus depends upon the fact that, at the temperature of the converter, Phosphate of Lime is not decomposed by metallic iron.

In the acid process the removal of Phosphorus is impossible, because Phosphate of Iron, assuming it to be formed in the presence of a silicious slag and molten iron, is immediately decomposed, and the Phosphorus passes back into the metal. The basic lining theoretically takes no part in this reaction, except in so far as it provides a non-silicious lining, and enables a very basic slag to be formed by additions of lime; but a neutral lining of Chrome iron ore, or similar material, would—provided it could resist the high temperature and mechanical abrasion of the metal, and if lime were added, in sufficient excess to combine with the Phosphorus, Silica, &c.—answer the same purpose. Part of the lining is always fluxed and part is abraded, thus assisting to form the slag, but this is accidental; and the object of making lime additions is to form a basic slag as early in the blow as possible, and so protect the linings of the vessels from this action.

The amount of lime that is added must vary with the composition of the metal; the more silicious and Phosphoric the pig-iron, the larger the quantity of lime required.

Pig-Iron Requirements for Basic Practice.—A good basic pig for Bessemer work should contain about 0·50 per cent. of Silicon, and never more than 1·00 per cent. As sulphur is removed only to a limited extent during the basic blow, and as its removal is somewhat erratic, it is necessary, in making basic pig, either to smelt Manganiferous iron ore, or to mix some Manganese ore with the blast furnace burden, to insure obtaining a pig iron low in sulphur; with the result that the best pig-iron of this class usually contains about 2 per cent. of Manganese. The percentage of Phosphorus is important, as in working with a low Silicon pig-iron, Phosphorus, Manganese, and Carbon are the only elements relied upon as fuel for raising the bath of metal to the required temperature for teeming. In other words, a certain percentage of Phosphorus is as essential to the basic Bessemer as a certain percentage of Silicon is to the acid Bessemer. In actual practice, about 2·5 to 3·00 per cent. of Phosphorus in the pig-iron is found to give the best results, as with a lower percentage than this, unless the Silicon is high, there is considerable danger of getting "cold heats." Pig-iron containing

much less Phosphorus than this has been frequently employed, but it does not give satisfactory results. Another important point with reference to Phosphorus is the question of the percentage of Phosphoric Acid in the slag, for, apart from any metallurgical considerations, it is of vital importance, from a commercial point of view, to obtain a slag rich in Phosphoric Acid, as otherwise its value for agricultural purposes is greatly reduced.

Purity of the Lime.—It is very important that the lime employed should be as free as possible from Silica, as every pound of Silica may be said in general terms to require 4 lbs. of lime to flux it, so that each per cent. of Silica in the lime entails a loss of 5 per cent. on the weight of lime added, and it also appears to retard the removal of sulphur. In many works lime, with Silica not exceeding 1 to 1·5 per cent., is used, although generally it amounts to 2 per cent., and sometimes considerably more.

Oxidation of Impurities.—The following series of analyses by Stead (Table xv.) of metals and slags taken during a low Phosphoric basic Bessemer blow, show the general changes taking place, and the curve, in fig. 86, which has been deduced from a number of published and private analyses, shows graphically the gradual oxidation of the impurities with more Phosphoric iron :—

TABLE XV.—Analyses of Metal Taken at Different Periods of the Basic Bessemer Process.

Period from Commencement.	Carbon.	Manganese.	Silicon.	Sulphur.	Phosphorus.	Copper.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Fluid Iron, -	3 57	0·71	1·70	0·06	1·57	Trace.
3 mins., - -	3·68	0·62	0·81	0·06	1·60	,,
6 ,, - -	3·40	0·56	0·28	0·06	1·63	,,
9 ,, - -	2·35	0·38	0·05	0·05	1·43	,,
12 ,, - -	0·88	0·27	0·01	0·05	1·42	,,
14½ ,, - -	0·07	0·12	Trace.	0·05	1·22	,,
16½ ,, - -	Trace.	0 10	Nil.	0·05	0·14	,,
16 ,, 35 secs.,	Trace.	Trace.	Nil.	0·05	0·08	,,

Analyses of Slag Taken at Different Periods of the Basic Bessemer Process.

	Silica.	Phosphoric Acid.	Metallic Iron.
	Per cent.	Per cent.	Per cent.
3 minutes, - - - -	32·60	0·60	5·65
6 ,, - - - -	42·60	1·15	2·00
9 ,, - - - -	36·00	1·60	4·60
12 ,, - - - -	35·60	2·61	4·80
14 ,, 30 seconds, -	33·00	5·66	6·15
16 ,, 30 ,, - -	15·60	15·06	10·45
16 ,, 35 ,, - -	16·60	16·03	11·35

The analyses were made from fused slag, not from a mixture of lime and scoria.

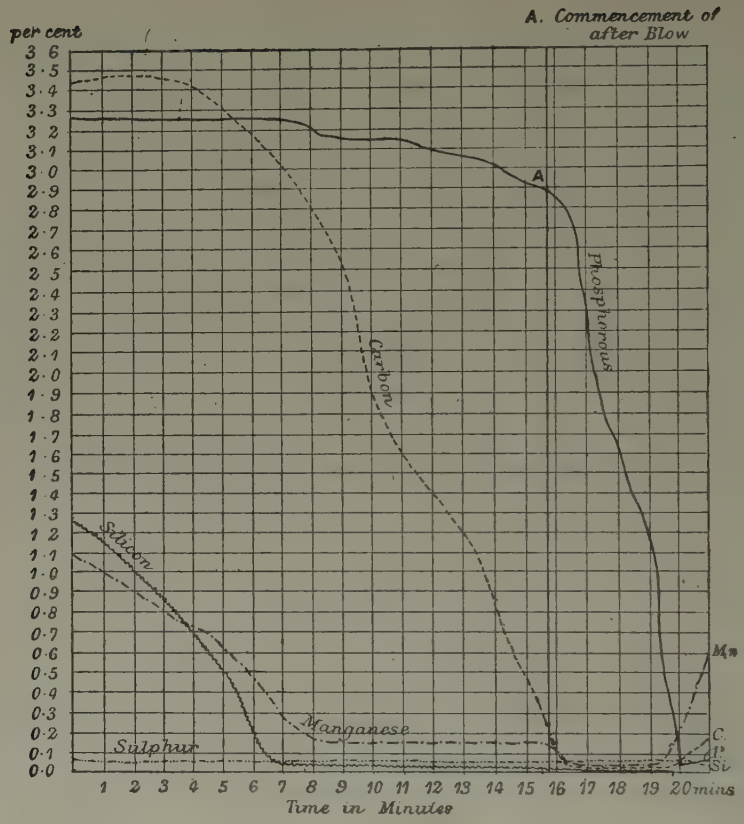


Fig. 86.

Silicon and Manganese.—The Silicon is the first of the constituents to be attacked during the blow, and is almost entirely oxidised during the first few minutes—*i.e.*, before the Carbon begins to disappear rapidly. The Silicon is much more completely removed than in the acid process, probably in part owing to the lower temperature resulting from the addition of considerable quantities of lime, and also to its affinity for so strong a base as the latter. Manganese passes out rapidly from the commencement of the

Blow No.	Description.	In Metal.	
		Mn.	*P.*
184	Disappearance of spectrum line—*i.e.*, commencement of after-blow,	0·19	2·070
	Second lime addition,	0·62	0·463
185	Disappearance of spectrum line,	0·24	2·180
	Second lime addition,	0·81	0·718
186	Disappearance of spectrum line,	0·24	2·390
	Second lime addition,	0·79	0·483

blow, but is not so completely removed as in the acid process. Stead * has shown that Phosphide of Iron is capable of reducing Oxide of Manganese when the two are melted together in a basic-lined crucible, and the above results given by Wedding † show that Manganese is reduced from the slag, and passes back into the metal during the basic after-blow, although it is to a great extent re-oxidised before its termination (see table, p. 94).

It can hardly be assumed that, under the oxidising conditions existing during the after-blow, Oxide of Manganese is reduced, but on stopping the blast and adding lime it appears that either the Phosphide of Iron present, or the mass of iron at the high temperature has a greater affinity for Oxygen than the Manganese, and these are able to act as reducing agents. From Stead's experiment, quoted above, it seems probable that the Phosphide of Iron, in the presence of large excess of lime, acts as the reducing agent.

Although the author has never verified this passing back of Manganese in the basic converter, he has done so repeatedly in the basic Siemens process, and there is no donbt that, owing to the presence of a powerful base like lime, the Oxide of Manganese is much more readily reduced from the slag than it is from the silicious slag in the Bessemer acid process.

Sulphur and its Elimination.—The behaviour of Sulphur during the blow is somewhat erratic, in certain cases a considerable proportion being removed, while at other times the elimination is hardly perceptible. The percentage removed is much more marked in cases of charges high in Sulphur than in those low in Sulphur, but the conditions most favourable are somewhat difficult to determine, and the results obtained by numerous metallurgists vary greatly when working under apparently similar conditions.

C. H. Ridsdale, after a long experience at the North-Eastern Steel Coy.'s Works, states that with pig-iron containing 1½ per cent. of Manganese, 0·09 per cent. of Sulphur is reduced to 0·06 per cent., and this confirms the author's experience. Stead ‡ has summarised the results of various investigators, as to the removal of Sulphur in basic Bessemer from pig-iron containing different percentages as follows:—

Sulphur in Pig.	Sulphur in Steel.	Percentage of Sulphur Removed.
0·420 per cent.	0·150 per cent.	64 per cent.
0·307 ,,	0·085 ,,	73 ,,
0·160 ,,	0·100 ,,	37 ,,
0·090 ,,	0·060 ,,	33 ,,
0·050 ,,	0·050 ,,	Nil.

Stead § found that fluid Oxides of Iron remove Sulphur from iron without the formation of Sulphur Dioxide, and he has also brought experimental evidence to show that the Sulphur in Sulphide of Iron is, in the presence of a fluid calcareous slag, converted into Calcium Sulphide. He contends that this is the reaction which takes place in the converter, the whole of the Sulphur being retained by the slag. Wedding,‖ on the

* *Iron and Steel Inst. Journ.*, 1893, vol. i., p. 66.
† *Ibid.*, 1890, vol. ii., p. 539.
‡ *Ibid.*, 1892, vol. ii., p. 283.
§ *Ibid.*, 1893, vol. i., p. 49.
‖ *Ibid.*, 1890, vol. ii., p. 539.

other hand, distinctly states that a considerable amount of Sulphur is volatilised during the blow, and that the total percentage of Sulphur in the original charge of metal is not accounted for by the percentage of Sulphur found in the slag. This statement refers to high sulphur charges, and as no data are given it is impossible to say on what evidence it is based; but coming from so high an authority it must be assumed that it can be supported by experimental evidence. It is possible that both authorities are right and that whereas, under normal conditions of work, with a highly basic slag, and when dealing with metal containing Sulphur under 0·20 per cent., as in Stead's experiments, the whole of the Sulphur may be found in the slag; with a less basic slag and higher Sulphur contents in the bath of metal some of the Sulphur may escape.

Wedding's results confirm those of Stead as to the removal of Sulphur taking place almost entirely during the "after-blow," and he cites one instance where desulphurisation was greatly increased by prolonging the "after-blow" slightly after complete dephosphorisation, which supports the contention that the Oxide of Iron formed plays an important part in the elimination.

Hilgenstock * disputes the deductions drawn by Stead, and maintains that Sulphate of Lime is produced in the Bessemer converter, and that the irregular removal of Sulphur in the basic Bessemer is due to the decomposition of this Sulphate by the iron bath and its re-absorption by the molten metal. In the author's opinion Stead has proved his case, at all events so far as to show that the final result is that Sulphide of Calcium is produced in the basic converter, and Sulphur retained in the slag in that combination. In whatever form the Sulphur may be removed, it has been clearly shown by Messrs. Wedding, Stead, Ridsdale, and others that its removal takes place practically during the "after-blow;" this is just what might be expected, as then there is the production of Oxide of Iron in excess, a very high temperature in the bath, and at the same time a very fluid calcareous slag.

In the early stages of the blow the Oxides of Iron produced are rapidly reduced by the Carbon, Silicon, &c., and to a less extent by other constituents present, and the temperature of the converter is such that only a comparatively small part of the lime has as yet been dissolved in the slag, so that a fluid calcareous slag is not formed until the "after-blow." There is no doubt that the fluidity of the slag plays a most important part both in desulphurising and dephosphorising, and it is probably largely due to the fluidity that the presence of Calcium Chloride confers on the slags that the Saniter desulphurising process owes its success.

TABLE XVI.—Analyses of Metal.

Description.	Metal.	1st Period.	2nd Period.	3rd Period.	4th Period.
		Desiliconised.	Decarburised.	Dephosphorised.	Steel.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Carbon, - -	2·32	2·180	0·07	0·02	...
Manganese, -	0 66	0·200	0·09	0·06	...
Silicon, - -	1·57	0·300	0·07	Trace.	...
Sulphur, - -	0·16	0·148	0·16	0·08	0·070
Phosphorus, -	1·85	1·920	1·53	0·04	...

* *Stahl und Eisen*, Jan. 15, 1893.

CORRESPONDING SLAGS.

Description.	1st Period.	2nd Period.	3rd Period.	4th Period.
	Desiliconised.	Decarburised.	Dephosphorised.	Steel.
	Per cent.	Per cent.	Per cent.	Per cent.
Lime,	44·30	47·00	46·78	...
Magnesia,	0·72	0·86	1·80	...
Manganous Oxide,	6·60	4·46	2·51	10·79
Ferrous Oxide,	4·38	8·23	14·02	9·00
Ferric Oxide,	1·29	1·00	4·29	2·14
Alumina,	0·35	0·26	0·30	...
Silica,	39·20	29·80	14·90	...
Phosphoric Anhydride,	2·61	7·83	14·86	...
Sulphur,	0·16	0·10	0·36	0·36
Phosphorus,	1·14	3·41	6·49	...
Probable per cent. of liquid slag on 100 parts of metal,	7	11	27·00	...
Sulphur in lime used = 0·054 per cent.				

The foregoing analyses by Stead (Table xvi.) from samples supplied by J. P. Walton show the removal of impurities during the basic blow with special reference to that of Sulphur. They also show that the entire amount of Sulphur present in the metal can be accounted for in the slag.

Assuming that the weight of slag per cent. of metal used was as given, we have the following sulphur account up to the end of the after-blow :—

SULPHUR IN SLAG.	Sulphur. Per cent.
27 per cent. of slag, at 0·36 per cent. Sulphur,	0·097
Less Sulphur added in the lime, 15·2 per cent., at 0·054 per cent. Sulphur,	0·008
Total received from metal,	0·089

SULPHUR REMOVED FROM METAL.	Sulphur. Per cent.
100 parts of raw iron contained,	0·160
Less 85 parts of blown metal, at 0·080 per cent. Sulphur,	0·068
Total removed,	0·092

The Sulphur removed during the fore-blow, calculated from the analyses of the slags, is as follows :—

AFTER FIRST PERIOD.

The Sulphur in 7 per cent. slag, at 0·16 per cent. Sulphur, less 0·025 carried in by the lime, is equal to, 0·009 on 100 of metal.

AFTER SECOND PERIOD.

The Sulphur in 11 per cent. slag, at 0·10 per cent. Sulphur, less 0·026 carried in by the lime, is equal to, 0·008 on 100 of metal.

The following results, obtained by C. H. Ridsdale, of the North Eastern Steel Works, have confirmed the above :—

Description.	Sulphur in Metal.	Sulphur in Slag.
	Per cent.	Per cent.
1. Metal poured into vessel,	0·100	...
2. After blowing five minutes,	0·118	...
3. At the drop of flame,	0·118	...
4. At first sampling,	0·074	0·377
5. At finish of blow before adding Ferro-Manganese,	0·071	0·391
6. Steel taken fifteen minutes after No. 5,	0·057	0·480

It has been experimentally shown by Finkiner,* and confirmed by Hilgenstock and Stead, that Sulphate of Lime is decomposed by iron at high temperature, and indirectly this has an important bearing on the elimination of Sulphur in basic Bessemer practice, as when impure lime containing appreciable quantities of Sulphate of Lime is used for making additions, not only is no Sulphur removed from the metal, but some Sulphur actually passes from the slag into the metal. The importance of using a pure lime in this connection was pointed out by Mr. J. P. Walton,† who considers that the removal of Sulphur in the Bessemer converter largely resolves itself into a question of the purity of the lime employed. He found that with a non-silicious lime low in Sulphur, Sulphur was removed from the metal, while with a silicious lime high in Sulphur, the latter element passed from the slag into the metal. With lime containing from 2·5 to 3·5 per cent. of Silica, and 0·27 to 0·35 per cent. of Sulphur, he found, as the result of three experiments, that there was practically no elimination of Sulphur from the bath; but with an exceptionally pure lime, containing 0·4 per cent. of Silica and only traces of Sulphur, the Sulphur was reduced from 0·064 to 0·02, and 0·03 per cent. in the finished steel. On the other hand, he found that when compelled to use a lime containing 5 to 6 per cent. of Silica and 0·7 to 1·00 per cent. of Sulphur, the Sulphur increased from ·06 per cent. in the cupola metal to 0·13, and even 0·20 per cent. in finished steel. The author's experience at the Staffordshire Steel and Ingot Iron Co.'s Works completely confirmed Mr. Walton's results, as under ordinary conditions a very pure Welsh lime was available, with the result that Sulphur was very appreciably eliminated during the blow; but on one or two occasions, when impure local lime was employed, owing to non-delivery of the usual material, considerable trouble was experienced with the increase of Sulphur in the finished steel.

It may be taken as generally admitted, that a fluid calcareous slag is the main factor in the elimination of Sulphur, while the fact that a certain amount of Sulphur passes out of the metal after the addition of the Ferro-Manganese, shows that Manganese plays some part in the elimination. Whatever the reaction is, it is probable that the Manganese which passes to and from the slag during the after-blow, as shown by Wedding, assists in the removal of the Sulphur. It may be a direct reduction of the Ferrous Sulphide by the Manganese, with formation of the Sulphide of Manganese, this being assisted by the fluid calcareous slag; or it may be an indirect reaction, the Manganese Oxide formed increasing the fluidity of the slag, and enabling the calcareous slag to act more effectively on the metal. So far as the author is aware, no direct experimental evidence elucidating the particular reaction in the converter can be adduced. We know that in the metal mixer Sulphur is directly eliminated as Sulphide

* *Mittheilungen aus den Königl. technischen Versuchsanstalten zu Berlin*, 1893, p. 28, *et seq.*

† *Iron and Steel Inst. Journ.*, 1893, vol. i., p. 90, *et seq.*

of Manganese, on the addition of Manganiferous iron to high Sulphur iron, and this distinctly supports the hypothesis of removal as Sulphide of Manganese. On the other hand, there is considerable evidence that by increasing the fluidity of a calcareous slag, the removal of Sulphur is effected apart from the presence of Manganese.

Phosphorus.—In the early days of the basic Bessemer process, pig-iron containing from 1·5 to 2 per cent. of Phosphorus was frequently used, but as the metal had necessarily to be low in Silicon, it was soon found that, even with the greatest care, there was considerable risk of the metal becoming too cold for tapping, and the loss from skulling was considerable, consequently a more Phosphoric pig-iron was soon generally adopted. To obtain the necessary heat in the finished metal, with pig-iron containing 0·5 per cent. of Silicon, the Phosphorus should not be less than 2·5 to 3 per cent.—preferably the latter—and in some works pig with 3·5 to 3·8 per cent. of Phosphorus has been regularly used without in any way deteriorating the quality of the finished steel.

As the Phosphorus is not appreciably removed until all the other impurities have been eliminated, the heat from its oxidation is concentrated at the end of the blow, when it is most required, and thus it compensates for the absence of Silicon, the great heat producer in the acid Bessemer.

The curves in fig. 87, taken from Wedding, together with general curves on p. 94, show the rate of oxidation of the Phosphorus in pig-irons containing different percentages of this element, and it will be seen that only about 10 per cent. is, on an average, removed before the after-blow commences. It cannot, of course, be assumed, in view of the strong affinity which Phosphorus has for Oxygen, that the Oxygen of the blast, or the Oxide of Iron formed, especially selects the Silicon, Carbon, and Manganese for oxidation during the first part of the blow, and then attacks the Phosphorus. There can be little doubt that the Phosphorus is oxidised from the commencement of the operation at the same time as the other elements, but that in the absence of a basic fluid slag rich in lime, the Phosphate of Iron is immediately decomposed in the presence of an excess of iron containing Carbon. Stead * in 1879, by a very pretty experiment, showed clearly that this was so.

He melted Cleveland pig in a large lime-lined crucible, impinged upon the surface a jet of air, and as the Oxide was formed, he absorbed it with a lump of lime, and found it to consist largely of Phosphate of Iron. When the blast was stopped, the surface of the metal rapidly cleared, the Oxide and Phosphate of Iron being reduced by the Carbon in the metal, before it could reach the sides of the crucible to be absorbed by the lining, and it was only when the metal was practically decarburised that the Oxide formed on the surface ceased to be reduced.

In the Bessemer converter, Phosphate of Iron is formed near the twyers, but in passing through the bath of metal, it is reduced by the Carbon, Silicon, &c., in the mass of metal before it can reach the slag. Stead found that it was impossible to dephosphorise to the slightest extent at the high temperature existing in an acid Bessemer converter, even when over-blowing was continued for fifteen minutes, but if lumps of ferruginous slag, containing over 50 per cent. of Oxide of Iron and 39 per cent. of Silica, were stirred into fluid Cleveland pig-iron, 50 per cent. of the Phosphorus was removed, showing that temperature was a very important factor effecting the reaction.

Sir Lowthian Bell, in 1878, by running metal into a bath of molten Oxide of Iron in a furnace lined with "Blue Billy," demonstrated most clearly that at comparatively low temperatures Oxide of Iron was capable of removing

* *Proceed. Inst. Cleveland Engineers*, 1879, p. 62.

the greater part of the Phosphorus from pig-iron, the Carbon being removed only to a small extent. The actual results obtained were the removal of 95 per cent. of Silicon, 84 per cent. of Phosphorus, and only 11 per cent. of

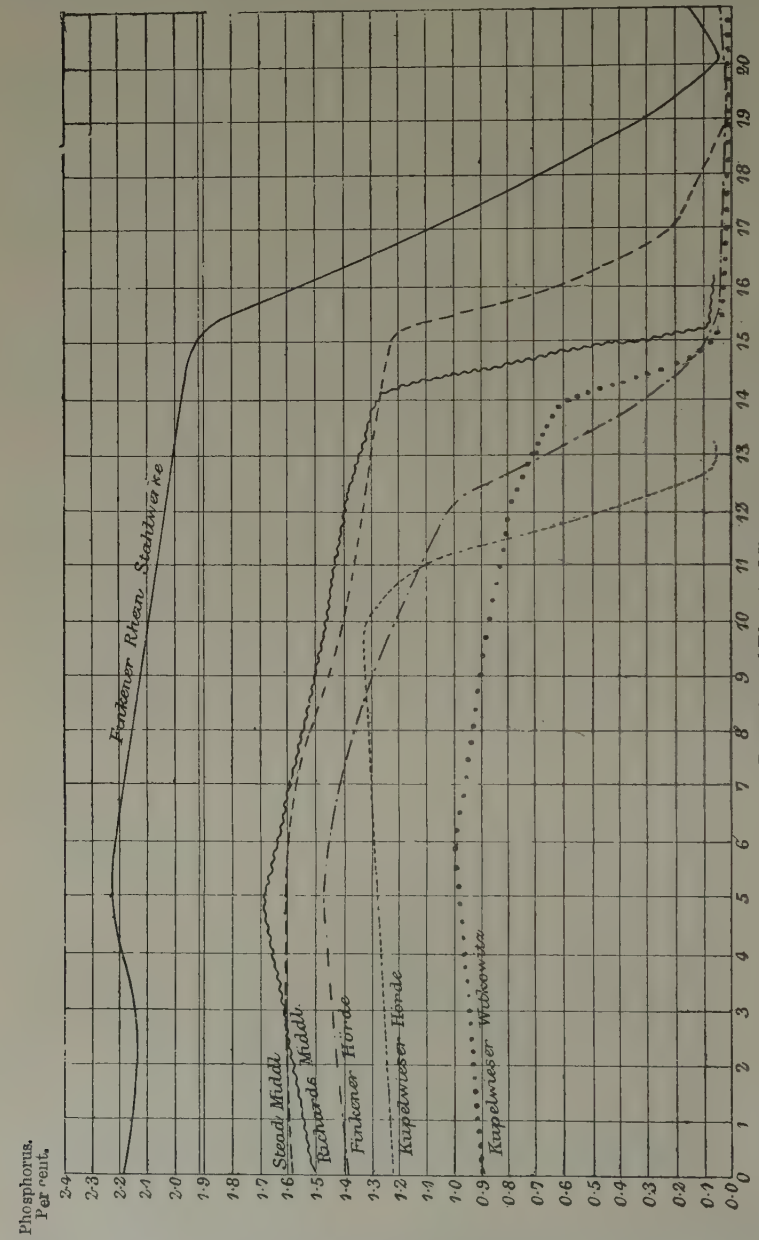


Fig. 87.—Removal of Phosphorus in Basic Bessemer from Iron containing varying percentages of Phosphorus. Curves plotted by Wedding.

Carbon. In this particular experiment there were conditions similar to those prevailing in the basic Bessemer during the early part of the blow,

except that in the latter case the temperature is higher, and the proportion of Oxide of Iron to metal less.

There seems little doubt that if it were possible to keep the temperature of the converter metal only slightly above that of molten pig-iron, dephosphorisation would result from the commencement of the blow, or, at all events, as soon as the Silicon was removed and sufficient Oxide produced in excess to form Phosphate of Iron. Owing, however, to the high temperature prevailing, any Phosphate of Iron formed is reduced by the metallic bath, sufficient lime not being dissolved in the slag to combine with and hold it. Towards the end of the blow, the conditions as regards basicity of slag are changed, as with increasing temperature the slag increases greatly in fluidity and absorbs more lime. After the removal of Carbon, Silicon, and Manganese, the metal bath is more readily oxidised, with the result that the large excess of Oxides of Iron and Manganese rapidly oxidises the Phosphorus; and the Phosphate of Iron thus formed, being brought into intimate contact with a very fluid slag, rich in lime, gives up its Phosphorus to the latter, with the production of a Phosphate of Lime,* a compound which is not appreciably reduced by metallic iron at the temperature of the converter. It has been shown by Messrs. Hilgenstock, Stead, Ridsdale, and others, that the Phosphoric acid exists in the slag in combination with four atoms of lime to one of Phosphoric Acid—that is to say, as tetrabasic Phosphate of Lime, $4\,CaO P_2O_5$; but to ensure the formation of a stable Phosphate, it is necessary that lime should be present considerably in excess of that theoretically required to form this Phosphate.

Rephosphorisation of Metal on Addition of Spiegel, &c.—On adding Spiegeleisen or Ferro-Manganese at the end of the blow, it is found that the Phosphorus is to some small extent reduced from the slag, and passes back into the metal, so that it is practically impossible to make high Carbon steel by means of additions of Spiegeleisen in the converter. The difficulty is overcome to some extent by pouring off the great bulk of the slag before making the Manganese additions, or by adding the latter in the ladle, the slag being kept back as much as possible in the converter during pouring. Different explanations have been given of the reason of this reduction, it being generally held to be due to the **CO** given off, and to the reducing action of the Manganese itself.

Stead, on heating basic slag at a very high temperature in an atmosphere of Carbon Monoxide, obtained buttons of iron free from Phosphorus, showing that the iron, but not the Phosphorus, had been reduced. Again, on simultaneously melting equal quantities of Ferro-Manganese and carburetted iron in separate crucibles in the same furnace with similar proportions of Phosphate of Lime, he found that the button of metal obtained from the Ferro-Manganese contained 1·0 per cent. of Phosphorus, that from the carburetted iron only 0·1 per cent. In another experiment, by increasing the length of time in the furnace, he obtained a Ferro-Manganese button containing as much as 5 per cent. of Phosphorus.

The heat of formation of Phosphide of Manganese is considerably greater than that of Phosphide of Iron, and consequently we should expect that Manganese would be a more powerful reducing agent than iron for Phosphate of Lime.

These experiments seem to point very strongly to the probability that Manganese acts as a direct reducing agent on the Phosphoric

* Stead has shown that when Phosphate of Iron and Lime are heated together, Phosphate of Lime and Oxide of Iron are obtained. *Proceed. Inst. Cleveland Engineers*, 1879, p. 59.

Acid in the slag, and that the Carbon Monoxide given off takes little part in the reduction, although by agitating the bath and bringing metal and slag into intimate contact it assists indirectly. It has been mentioned that Stead found that Phosphide of Iron would reduce Oxide of Manganese, and that this Oxide is certainly reduced during the Bessemer blow from the slag. Consequently, if the above reaction takes place, Manganese then is acting, on the one hand, as a reducing agent, and Oxide of Manganese acting under similar conditions as an oxidising agent and being itself reduced. Although the conditions during the after-blow and at its finish are similar, they are by no means identical, and the difference in temperature, together with the Silicon in the Ferro, and the presence of the reducing Carbon Monoxide gas given off, may constitute just sufficient variation to cause a reversal of the chemical reaction, a phenomenon which in many other cases is simply a matter of temperature. Whatever the exact cause of this reduction of Phosphorus, it cannot be entirely prevented, but it may be largely reduced by maintaining a very calcareous slag, as the more basic the slag, the less readily will the Phosphoric Acid be removed from it.

Re-carburisation in the Basic Bessemer Process.—Owing to the tendency to over-oxidation during the basic after-blow, somewhat larger quantities of Ferro-Manganese or Spiegel are required than in a corresponding acid blow, and numerous attempts have been made to decrease this by adding carbonaceous matter in various forms to reduce the excess of Oxides before adding the Ferro-Manganese. Basic material mixed with tar and other carbonaceous matter, made into compact bricks by coking, and wooden boxes filled with carbonaceous matter and pig-iron to weight them have been tried, but not generally adopted. Grey hematite previously heated to a red heat, in the case of soft steel, is frequently used, and probably this is about the best practice and is the one most generally followed. The use of a good manganiferous pig-iron for blowing is the best method for reducing the quantity of finishing metal required, as when this is used some Manganese, often as much as ·2 or ·3 per cent., is left in the metal at the end of the blow, and tends greatly to reduce the over-oxidation. In the case of rail steel, when Carbon from 0·35 to 0·45 per cent. is required, Spiegel melted in a small cupola and run into the ladle, or else some modification of the Darby process (p 189) of recarburising is employed. The economy of using the latter for these comparatively low Carbon steels is more apparent than real, since 15 per cent. Spiegel can now be bought at practically the price of rail steel. As every cwt. added to the charge contains 94 per cent. of mixed metals, Iron and Manganese, this means so much more weight in the ingots; whereas, when Carbon only is added, although the actual cost of material is practically nil, the increase in weight only equals the percentage of Carbon actually absorbed. The percentage of iron in the slag is a matter which, in many works, does not receive the attention which it deserves, but it is a most important point, and furnishes a very good indication as to whether the operation of blowing is being conducted with care. In a works producing 500 tons of slag per week, an increase of Oxide of Iron equal to 2 per cent. of iron in the slag means a loss of 10 tons of steel, which, at a very low estimate, is equal to £30 per week, and this is very likely to occur if the working of the process is not controlled by frequent analyses of the slag, and every precaution taken to keep the amount of Oxide present as low as possible. The amount of Oxide of Iron in the basic slag at the end of the blow should not, as a rule, exceed 13 per cent., equal to about 10 per cent. of metallic iron.

Effect of Oxide Additions.—It has already been pointed out that it is most important to obtain a fluid slag as early as possible in the blow, and, if in addition to this, the yield per ton of pig-iron used can be increased, two very important points will have been gained. This may to some extent be effected by adding easily fusible Oxides of Iron with the lime before putting the metal into the converter, when there is little doubt that a considerable proportion of such Oxides is reduced by the metalloids in the pig-iron, in the same way that the Oxides formed at the twyers are reduced. In some works as much as 10 cwts. of Oxide are added to a 7-ton charge, without the resulting slag containing any more iron than in similar charges blown without such additions, and it is not an unusual practice to add 1 cwt. of Oxide per ton of metal, part with the first lot of lime, and part just before the after-blow. The advantage of adding some Oxide just before the after-blow is that the fluidity of the slag is increased, and this tends to shorten the after-blow, and also to remove the Phosphorus more completely. The objection to doing this is that there is a possibility of obtaining an oxidising slag which tends to produce red-short metal, unless larger additions of Ferro are made; but this view does not seem to have been borne out by experience. It is important that the Oxides added should be non-silicious, and good mill-furnace cinder from basic slag, or Oxide bottoms, answers admirably, and may be mixed with mill or hammer scale.

Thermo-Chemistry of the Acid and Basic Bessemer Processes.

All chemical action is accompanied by a redistribution of energy in the reacting bodies. Some of this energy takes the form of heat, and as the amount of heat liberated and absorbed during any reaction is invariable, and can be measured, the thermal aspects are as important in some respects as the chemical and physical aspects. When two bodies, such as Carbon and Oxygen, combine to form Carbon Monoxide (CO) or Carbon Dioxide (CO_2), a certain number of heat units are evolved; and when the CO or CO_2 is dissociated or split up again into its two elements, Carbon and Oxygen, the same number of heat units are absorbed. In general terms, a heat unit may be defined as the amount of heat required to raise a given weight of water through a given temperature. The weight of water taken in the following calculations is 1 kilogramme, and the heat unit employed is the quantity of heat required to raise 1 kilogramme* of water from 15° C. to 16° C., and when 50 heat units are said to be evolved it means that sufficient heat has been developed to raise 50 kilogrammes of water from 15° C. to 16° C. This heat unit is termed a Calorie. When Carbon and Oxygen combine in the proportion of their chemical equivalents to form CO_2, we have 12 parts of Carbon uniting with 32 of Oxygen, and when 12 grammes of Graphite are burned to CO_2 it has been found experimentally that the evolution of heat is 97·6 calories, so that this reaction may be expressed by the following equation:—$C + O_2 = CO_2 + 97{\cdot}0$ heat units or calories.

Here 97·6 heat units are evolved or given out, and this is termed an *exothermic* reaction—that is to say, the heat disturbance is positive, and this, in equations, is denoted by a + sign.

If, on the other hand, we oxidise Carbon by means of steam, as is done in making water-gas, the total result of the reaction is an absorption of heat; and if heat is not supplied from an independent source the reaction ceases, thus—

* Some writers base the calorie on 1 gramme of water, and call it "therm"; but the kilogramme calorie is used as more convenient for our purpose.

$$\underset{12\text{ grms.}}{C} + \underset{18\text{ grms. (58·2, heat of formation).}}{H_2O} = \underset{28\text{ grms. (29·4, heat of formation).}}{CO} + \underset{2\text{ grms.}}{H_2}.$$

That is to say, there are 29·4 heat units evolved by the combustion of Carbon to CO – 58·2 units absorbed in splitting up the water into O and H, so that the final result is that there is a loss of 28·8 heat units, which explains why it is necessary to supply heat by forcing air into a water-gas producer after steam has been oxidising the Carbon for a few minutes. This reaction, then, and all those which are attended with absorption of heat, are termed *endothermic*, and the result of the redistribution of heat is denoted by a – sign.

In considering these heat reactions the physical state of the bodies reacting, and also that of the products, whether solid, liquid, or gaseous, must be taken into account, and also the temperature at which the reaction takes place. This latter is important to remember, as a reaction which at one temperature may be attended with an evolution of heat may at another temperature result in heat being *absorbed*. Thus CO in burning to CO_2 at a comparatively low temperature evolves 68·2 heat units, but at a temperature approaching 3,000° C. only 37·0 heat units; and if we consider the reduction of Fe_3O_4, or Magnetic Oxide of Iron, by CO at a low and high temperature respectively, we get the following:—

The heat of formation of Fe_3O_4 is 270·7 heat units—that is to say, that three equivalents of Iron (56 × 3 = 168 grammes), on being oxidised to Fe_3O_4, evolve 270·7 heat units, and consequently 270·7 units will be absorbed when it is reduced. Carbon Monoxide (CO) in burning to CO_2 evolves 68·2 units at low temperatures Then

$$\underset{270\cdot7}{Fe_3O_4} + 4\,CO = 3\,Fe + \underset{68\cdot2 \times 4}{4\,CO_2}.$$

In the reduction of Fe_3O_4 we get 270·7 units or calories absorbed, or – 270·7 units evolved. In burning 4 CO to 4 CO_2 we get 68·2 × 4, or 272·8 units.

Therefore the final result is

$$272\cdot8 - 270\cdot7 = 2\cdot1 \text{ heat units evolved.}$$

This is an exothermic reaction, and is denoted by + 2·1 If we consider the same reaction at temperatures near 3,000° C., the heat absorption by dissociation of Fe_3O_4 is the same, but the heat evolved by oxidation of CO to CO_2 is only 37 units instead of 68·2 units. Thus

$$\underset{270\cdot7}{Fe_3O_4} + 4\,CO = 3\,Fe + \underset{4 \times 37}{4\,CO_2} = -122\cdot7$$

shows a deficiency of 122·7 units.

If we assume that the iron is reduced to Ferrous Oxide only, the equation becomes

$$\underset{270\cdot7}{Fe_3O_4} + CO = \underset{3 \times 69}{3\,FeO} + \underset{37}{CO_2} = -26\cdot7 \text{ units;}$$

so that the reaction is still attended by an absorption of heat.

These reactions would then be endothermic, and this explains in part how reactions are reversible, a reducing action at one temperature ceasing to be so, and even becoming an oxidising one at another. Chemical reactions take place only within certain limits of temperature, which vary with the par-

ticular substances. Thus Carbon and Oxygen do not combine at ordinary atmospheric temperatures, and at extremely low temperatures even the most energetic of chemical actions practically cease. On the other hand, at extremely high temperatures most chemical compounds are dissociated.

On the heat of formation of a compound—that is to say, on the number of heat units evolved at its formation or which will be absorbed on its dissociation—will depend its stability when brought into contact with another body under conditions in which they can react upon each other. Thus an oxidised compound will resist or undergo reduction when brought into contact with a reducing agent, according as its heat of formation is greater or less than the heat of formation of the body which would result from its reduction. For instance, Manganese is able to reduce Magnetic Oxide of Iron, because the resultant Manganese Oxide has a greater heat of formation than the Oxide of Iron.

$$\underset{270{\cdot}7}{Fe_3O_4(+270{\cdot}7)} + 3\,Mn = \underset{328{\cdot}0}{Mn_3O_4(+328)} + 3\,Fe.$$

absorbed. evolved.

57·3 heat units in favour of Mn_3O_4.

This enables the action of Ferro-Manganese as a deoxidising agent to be understood.

These theoretical considerations have a very important bearing on the reactions taking place in the Bessemer and Siemens processes, and serve to explain why certain bodies are more readily oxidised than others, and form stable compounds in the slag, thus allowing the impurities to be removed from the iron. The heat developed is the heat evolved, as the result of chemical combination, minus any heat absorbed by the reduction of bodies added to bring about such oxidation. In the case of the Bessemer process, the oxidising agent is the free Oxygen of the air, and, consequently, if we assume for the present that the Carbon, Silicon, Sulphur, &c, &c., in the pig-iron are dissolved in the iron, and not in any way combined, the heat developed will be the sum of the heat units evolved by the oxidation of the impurities present. In the case of the Open Hearth or Siemens process, the oxidising agent after the bath is melted is the Oxide of Iron added, and the heat units finally produced will be the same as in the Bessemer process (assuming the composition of the bath to be the same), minus the heat units absorbed in reducing the Oxide of Iron. It is true that in the Bessemer process Oxide of Iron acts to a large extent as the oxidising agent; but this Oxide is formed at the twyers with evolution of heat, and exactly the same amount of heat is re-absorbed when it is dissociated and gives up its Oxygen to the impurities present, so that there is no loss, and the Oxide simply acts as an agent for conveying Oxygen to the bath. In calculating the actual heat developed in the Bessemer process, it is of course necessary to deduct the number of heat units carried away by the products of combustion, loss by radiation, &c., but, at best, only an approximation to the loss from these sources can be arrived at. The loss by radiation is fairly constant for all qualities of iron, if blown for the same length of time, and it is usual to neglect it altogether.

It is by no means necessarily correct to assume that the Carbon, Silicon, Sulphur, Phosphorus, Manganese, &c., exist in the free state in iron at high temperatures, as Carbides, Silicides, and Phosphides of Iron are well known. If these bodies are in chemical combination with the iron, they must, before they can be oxidised, be decomposed with absorption of heat, and such heat must be deducted from that evolved on their oxidation. Before, however, discussing the somewhat complex

question of the constitution of the pig-iron, it may be advisable to give the method of calculating the heat evolved on the assumption that the elements exist in the free state, and afterwards further consider the question in the light of more recent investigation.

The following data are necessary, so that an allowance may be made for the heat carried away by the products of combustion :—

Specific Heats: C = 0·241; CO = 0·2479; O = 0·218; H = 0·244; FeO = 0·17; molten pig-iron = 0·110; molten steel = 0·16; the two latter values being only approximations. The initial temperature of the molten pig-iron is 1,400° C., and the average temperature during the blow 1,700°. The air is supposed to be dry, so no correction is made for moisture. The composition of the pig-iron is assumed to be as follows :—

C = 3·5 per cent.; Silicon = 1·0 per cent.; Manganese = 1·5 per cent.; Phosphorus = 3·0 per cent.; 2 per cent of the iron will be burnt to FeO, according to Campbell's estimate.* For convenience of calculation, we may assume 1,000 kilos. to be blown.

The following are the heats of oxidation :—

				Heat Units or Calories.
Si + O_2,	*i.e.*, 28 grms. of	Si	combining with 32 grms. O	= 179·6.
C + O_2,	,, 12 ,,	C	,, ,, 16 ,,	= 29·4.
S + O_2,	,, 32 ,,	S	,, ,, 32 ,,	= 69·3.
P_2 + O_5,	,, 62 ,,	P	,, ,, 80 ,,	= 365·2.
Mn + O,	,, 55 ,,	Mn	,, ,, 16 ,,	= 91·0.
Fe + O,	,, 56 ,,	Fe	,, ,, 16 ,,	= 69·0.
Fe_3 + O_4,	,, 168 ,,	,,	,, ,, 64	= 270·7.

Heat developed from one kilogram of element.		Heat developed from one kilogram of element.	
C,	2,450	Mn,	1,654
Si,	6,414	Fe,	1,232 (Ferrous Oxide formed).
S,	2,166	Fe,	1,611 (Magnetic Oxide formed).
P,	5,890		

In 1,000 kilos. of metal of the above composition we have 35 kilos. of Carbon, 10 kilos. of Silicon, 15 kilos. of Manganese, 30 kilos. of Phosphorus, and 20 kilos. of iron to be oxidised, and thus the total heat evolved will be, in round numbers—

		Heat Units or Calories.
Carbon,	2,450 × 35	= 85,750
Silicon,	6,414 × 10	= 64,100
Manganese,	1,654 × 15	= 24,800
Phosphorus,	5,890 × 30	= 176,700
Iron,	1,232 × 20	= 24,640
Total heat evolved,		= 375,990

From these heat units must be deducted the heat units carried away in the gaseous products of combustion, and in the Nitrogen which passes away with them, and, also in the case of solid products of combustion, the heat absorbed in raising them to the temperature of the bath. It is assumed, for the purposes of calculation, that all the Carbon is burnt to CO, although, according to Snelus, about 17 per cent. is burnt to CO_2.

35 kilos. of Carbon require 46·7 kilos. of Oxygen, and produce 81·7 kilos. of CO. This necessitates the introduction of $\frac{46·7 \times 77}{23}$ kilos. of Nitrogen.

* *Structural Steel*, p. 73.

Therefore, the heat absorbed will be—

By Carbonic Oxide, $1,700\,(81{\cdot}7 \times 0{\cdot}2479) - (35 \times 0{\cdot}241)\,1,400 = 22,600$ calories.

By accompanying Nitrogen, $\frac{46{\cdot}7 \times 77 \times 1,700 \times 0{\cdot}244}{23} = 64,800$,,

By O for oxidation of Silicon to SiO_2, $11{\cdot}43 \times 0{\cdot}218 \times 1,700 = 4,200$,,

By accompanying Nitrogen, $\frac{11{\cdot}43 \times 77}{23} \times {\cdot}244 \times 1,700 = 15,800$,,

By O for oxidation of Manganese to MnO,

$(4{\cdot}364 \times 0{\cdot}218 \times 1,700) + \frac{4{\cdot}364 \times 77}{23} \times {\cdot}244 \times 1,700 = 7,600$,,

By O for oxidation of Phosphorus to P_2O_5.

$(38{\cdot}7 \times {\cdot}218 \times 1,700) + \frac{38{\cdot}7 \times 77}{23} \times {\cdot}244 \times 1,700 = 68,000$,,

By O for oxidation of iron to FeO,

$(25{\cdot}7 \times {\cdot}17 \times 1,700) - (20 \times 0{\cdot}11 \times 1,400) + \left(\frac{5{\cdot}71 \times 77}{23} \times {\cdot}244 \times 1,700\right) = 12,300$,,

Total heat absorbed, 195,300 ,,

The heat remaining in the converter is, therefore, 375,990 – 195,300 = 180,690 calories.

Although the foregoing statement gives a general idea of the heat produced during a Bessemer blow, it is necessary to consider the view advanced by Professors Ponthière and Hartley, and other chemists and metallurgists as to the constitution of molten iron. Various Carbides, Silicides, and Phosphides of both iron and Manganese are well known, and the calculations of both Professors Ponthière and Hartley, on reactions in the Bessemer converter, are based on the assumption that some of the more stable of these exist in iron at the temperature of the Bessemer converter.

The researches of Troost and Hautefeuille* have shown that the Carbide, Silicide, Sulphide, and Phosphide of Manganese evolve a considerable amount of heat at the moment of formation, or, in other words, are stable bodies, while the corresponding iron compounds, with the exception of the Phosphide, are comparatively unstable. On this account we may assume that the Manganese exists in the pig-iron almost entirely as Carbide, Silicide, and Sulphide, and none in the free state. The Phosphides of Iron and Manganese are both stable bodies, so in this case we may assume that the Phosphorus is distributed between the iron and Manganese in the ratio of their masses—*i.e.*, practically all combined with the iron. The fact that both the Carbide and Silicide of Manganese are stable bodies, and that, as a rule, there is not sufficient Manganese present to combine with all the Carbon and Silicon, leaves us in doubt as to how these two elements are combined. Professor Ponthière† considers that we are justified in supposing that two-thirds of the Manganese is in the form of Carbide and one-third as Silicide, this being about the ratio of their respective heats of formation. The rest of the Carbon and Silicon will be combined with the iron. Carnot and Goutal‡ have also studied the constitution of cast iron, and have come to the following conclusions :—Sulphur is usually combined with Manganese as MnS, any excess being combined with the iron as FeS.

* *Annales de Chimie et de Physique*, 5th series, vol. ix., 1876.
† *Iron and Steel Inst. Journ.*, 1897, vol. ii.
‡ *Annales des Mines*, vol. xviii., pp. 263-300.

Phosphorus is combined directly with iron as Fe_3P. Silicon is usually free, but it can combine with Manganese and with iron, forming MnSi and FeSi respectively, the latter, however, is decomposed on slow cooling. Carbon is combined with both Manganese and iron, probably as $4\,Fe_3C$, Mn_3C, any excess of Carbon being combined with iron, forming Fe_3C.

On the above assumption, the constitution of the pig-iron that we have been considering would be as follows:—

Pig-Iron Analysis. Per cent.			Constitution of Molten Iron. Per cent.	Per cent.
C = 3·50 Si = 1·00 S = 0·02 P = 3·00 Mn = 1·50	Carbide of Manganese,	Mn_3C,	Mn = 1·00 C = 0·07	1·07
	Silicide of Manganese,	MnSi,	Mn = 0·50 Si = 0·25	0·75
	Phosphide of Iron,	Fe_3P,	Fe = 16·26 P = 3·00	19·26
	Carbide of Iron,	Fe_3C,	Fe = 46·34 C = 3·31	49·65
	Silicide of Iron,	FeSi,	Fe = 1·50 Si = 0·75	2·25
	Sulphide of Manganese,	MnS,	Traces	
	Free Iron,		...	27·02
				100·00

The heat developed by the oxidation of these compounds may be calculated in the following manner:—For the oxidation of Manganese Carbide the thermal equation is—

$$\begin{array}{cccccc} Mn_3C & + & 5\,O & = & 3\,MnO & + & CO_2 \\ x & & & & 3 \times 91 & & 97{\cdot}6 = 370{\cdot}6 - x \text{ calories,} \end{array}$$

or 370·6 calories, if x, the heat of formation of the Carbide, be zero.

If it is assumed that the Carbon is burnt to CO instead of CO_2, we get—

$$\begin{array}{cccccc} Mn_3C & + & 4\,O & = & 3\,MnO & + & CO \\ x & & & & 3 \times 91 & & 29{\cdot}4 = 302{\cdot}4 - x \text{ calories,} \end{array}$$

or 302·4 calories when $x = 0$.

In the same way we arrive at the following values of the heats of oxidation of the various constituents of the iron, assuming for the moment that the heat required to decompose them, or, in other words, their heat of formation is zero:—

TABLE XVII.—Heats of Oxidation.

Carbide of Manganese (burnt to CO_2),	370·6
,, ,, (burnt to CO),	302·4
Sulphide ,,	160·2
Silicide ,,	270·6
Phosphide of Iron,	129·9
Carbide of Iron (C burnt to CO_2),	101·5
,, ,, (C burnt to CO),	78·8
Sulphide of Iron,	138·2
Silicide of Iron,	248·6

In every case these values refer to a *gram-atom* of the metal. In order to arrive at the *true* heats of oxidation we must subtract from them the heats of formation of the various compounds. Unfortunately these heats of formation are not accurately known in many cases. The following table,

slightly altered from one by Professor Ponthière, gives approximations sufficiently close for the present purpose :—

TABLE XVIII.—Heats of Formation.

Carbide of Manganese,	Mn_3C, ...	114·4 calories.
Sulphide of Manganese,	MnS, ...	53·4 ,,
Silicide of Manganese,	MnSi, ...	47·4 ,,
Phosphide of Iron	Fe_3P, ...	43 3 ,,
Silicide of Iron	FeSi, ...	negligible.
Carbide of Iron,	Fe_3C, ...	negligible.

Subtracting these values from the values calculated on the assumption that the heats of formation are zero, we arrive at the results given in the following table :—

TABLE XIX.—Heats of Oxidation of the Constituents of Iron.

	Formula.	Heat of Formation.	Heat of Oxidation per grm.-atom of free metal.	Heat of Oxidation of Compound per grm.-atom of the metal in combination.
Silicide of Iron, ...	FeSi	Negligible	248·6	248·6
Carbide of Manganese (C burnt to CO_2),	Mn_3C	114·4	370·6	256·2
Sulphide of Iron, ...	FeS	24·0	138·2	114·2
Sulphide of Manganese, ...	MnS	53·4	160·2	106·8
Silicide of Manganese, ...	MnSi	47·4	270·6	223·2
Carbide of Iron (C burnt to CO_2), . .	Fe_3C	Negligible	101·5	101·5
Phosphide of Iron, ...	Fe_3P	43·3	129·9	86·6
Carbide of Iron (C burnt to CO), . .	Fe_3C	Negligible	78·8	78·8
Carbide of Manganese (C burnt to CO), .	Mn_3C	114·4	302·4	188·0

In the above table it has been assumed that the iron is burnt to Ferrous Oxide. This is certainly true to a large extent as will be shown, although the burnt metal contains Magnetic Oxide. In any case, the substitution of Magnetic Oxide for Ferrous Oxide would make only a slight difference to the above values.

To arrive at an accurate estimate of the heat evolved during oxidation, it would be necessary to add to the above the heat developed by the formation of the slag. In many cases the required data are wanting, and even the specific heat of the slag has not been determined. The following figures, however, are available :—

$Ca + O = CaO + 131{\cdot}5$ cal.
$Ca + S = CaS + 90{\cdot}8$,,
$CaO + SiO_2 = CaSiO_3 + 33{\cdot}3$,,
$FeO + SiO_2 = FeSiO_3 + 9{\cdot}3$,,
$4\,CaO + P_2O_5 = 4\,CaO.P_2O_5 + 180$,, (about).
$3\,FeO + P_2O_5 = 3\,FeO.P_2O_5 + 30{\cdot}6$,,

In view of the complex constitution of pig-iron at high temperatures, and the lack of exact knowledge of the form in which the foreign elements exist in it, the thermal calculations given above must be considered as an approximation only. Whether the elements exist in anything like the com-

bination suggested by Professor Ponthière, or by Carnot and Goutal, in the present state of our knowledge it is impossible to say, but we may, for the purposes of calculation, assume that they exist in some such form of combination, and therefore from any heat evolved must be deducted that absorbed in decomposing such compounds. In view of the progress which is being made in the analysis of pig-iron and other alloys, especially in respect to their ultimate composition, it is of importance that the student should cease to regard pig-iron as mere mixtures of Carbon, Silicon, Manganese, &c., with metallic iron, but should accustom himself to think of these elements as forming definite compounds with the iron.

The amount of heat evolved and absorbed by the decomposition and oxidation of the impurities in the Siemens process is the same as for the Bessemer process, but the total heat produced in the bath from metal of the same composition is less, owing to the oxidation being effected by **FeO** or Fe_2O_3, which has to be reduced with consequent absorption of heat; it must be remembered that the heat produced by the oxidation of the impurities is spread over some hours instead of being all evolved in a few minutes On the other hand, no heat is carried away by Nitrogen passing through the molten metal as in the Bessemer process.

The foregoing calculations derive real interest and importance from the fact that they enable us to give a reasonable explanation of many of the reactions occurring during the manufacture of steel by the Bessemer and Siemens processes.

Let us first consider Sulphur. It is well known that Sulphur is not removed during the acid-blow or in acid Siemens practice, and its removal is very irregular during the basic-blow and in basic Siemens practice. When Oxygen is blown through a bath of iron containing **FeS**, we should expect that **FeO** and SO_2 would be formed, and that the latter would pass away with the products of the combustion ; but the reason why this does not take place is shown by the following equation :—

SO_2	+	3 Fe	=	2 FeO	+	FeS	
69·3				2 × 69		24	= 92·7 calories.

Thus assuming SO_2 to be formed, it would immediately be reduced by the **Fe** and **FeS** re-formed, as its reduction is attended by the gain of 92·7 calories. If, however, we have lime present, the following reaction *may* take place :—

FeS	+	CaO	=	FeO	+	CaS	
24		131·5		69		90·8	= 4·3 calories.

This reaction, while exothermic, is very feebly so, and it explains why the removal of Sulphur, even under basic conditions, is very erratic.

It is also well known that the addition of Manganese does, under certain conditions, remove the Sulphur, or at all events mask its effects, and it is conceivable that if it remains associated with the metal it may be less injurious as **MnS** than in the form of **FeS**.

FeS	+	Mn	=	MnS	+	Fe	
24				45·6			= 21·6 calories.

This explains the removal of Sulphur in the metal mixer as **MnS**.

In the case of Phosphorus in the acid converter, or acid Siemens furnace, any Phosphate of Iron formed is at once decomposed either by Silicide of Manganese, if present, or by Metallic Iron. When no Manganese is present the Metallic Iron in excess is quite sufficient to explain the reaction. The

heat of formation of Ferrous Phosphate from its *elements* is 465 calories, so that we have

$$\underset{465}{3\,FeO,P_2O_5} + 11\,Fe = \underset{8 \times 69}{8\,FeO} + \underset{2(43{\cdot}3 \times 3) = 346{\cdot}8 \text{ calories.}}{2\,Fe_3P}$$

So that assuming that Phosphate of Iron or Phosphoric Anhydride is formed, the above thermal equation explains why it is immediately reduced with re-formation of Phosphide of Iron. If, however, we introduce a base, which, by its combination with Phosphoric Anhydride, evolves more heat than FeO, we ought to be able to replace the FeO by this base and form a more stable Phosphate. We have such a base in lime which forms a Tetra-Phosphate on uniting with P_2O_5, and evolves about 180 calories in so doing, so that we have the following reaction taking place :—

$$\overbrace{3\,FeO + P_2O_5}^{30{\cdot}6} + 4\,CaO = \underset{180}{4\,CaO,P_2O_5} + \underset{= 149{\cdot}4 \text{ calories.}}{3\,FeO}$$

Since the lime is already oxidised when added to the bath its heat of formation need not be considered, and we have the following equation for the action of excess of iron on Phosphate of Lime :—

$$*\,\underset{180 + 365{\cdot}4}{4\,CaO,P_2O_5} + 11\,Fe = \underset{345}{5\,FeO} + \underset{6(43{\cdot}3)}{2\,Fe_3P} + \underset{= 59{\cdot}4 \text{ calories.}}{CaO}$$

According to this equation, excess of iron is capable of reducing Phosphorus from the Phosphate of Lime, though the reaction is a feeble one compared with that between 3 FeO,P_2O_5 and excess of iron. It should be remembered, however, that the removal of the bulk of the Phosphorus does not begin until the Carbon and Manganese have been removed and the bath is free from these reducing agents. Its elimination is, therefore, probably due to mass action, the large excess of lime and air overcoming the reducing tendency of the free iron. We should, therefore, expect that, on stopping the blast and adding Ferro-Manganese, some of the Phosphorus would pass back, and this actually does occur to a limited extent in practice. In this connection it must be remembered that the heat formation of Phosphide of Manganese is considerably greater than that of Phosphide of Iron, and consequently Manganese would have a greater tendency than iron to reduce the Phosphorus from the slag. Although the above equations show which reactions are thermally possible, these reactions, like most others, depend largely on the temperature of the bodies reacting, and while Metallic Iron at the ordinary temperature of the Bessemer converter decomposes Phosphate of Iron, and to a less extent Phosphate of Calcium, at lower temperatures this is not the case, as is evident from Phosphorus being very largely removed, in the Bell and other washing processes, in combination with Oxide of Iron.

* It is possible that the heat of formation given—viz., 180 calories—is too low, the data for arriving at this figure not being very satisfactory.

CHAPTER VI.

GAS PRODUCERS.

THERE is probably no factor of more importance to the successful working of Siemens and other gas-fired furnaces than the economical production of good gas, and a great amount of attention has been given by many metallurgists and engineers to this subject, with the result that we have numerous gas producers very similar in general construction, but differing from each other in many little details, designed to give greater efficiency and economy.

Theory of the Gas Producer.—In all metallurgical operations which depend upon high temperatures the problem is to do the work with the least expenditure of fuel, and, theoretically, far greater efficiency should be obtained by the use of solid Carbon than by an equivalent weight of Carbon converted into gas. Thus, a kilogram of pure Carbon on complete combustion to Carbon Dioxide would evolve 8,080 heat units, but if first gasified to Carbon Monoxide, assuming there were no loss by radiation, &c., and then burnt to Carbon Dioxide, would only evolve 5,630 units, showing a difference of 2,450 heat units, or nearly one-third of the whole. So far as the final result is concerned, one-third of the total available heat energy of the Carbon is actually developed in the producer, and is lost in respect to subsequent metallurgical operations in outside furnaces, except such portion as may be utilised in dissociating injected steam. In other words, the total combustion of Carbon gives 8,080 heat units, the combustion of Carbon to Carbon Monoxide, which is the final product as it leaves the producer, evolves 2,450 heat units in the producer, leaving 5,630 units of heat to be evolved on combustion to CO_2 outside for every unit of Carbon gasified. The superiority of solid Carbon over gaseous fuel is based on the assumption that the conditions are such that perfect combustion of the solid Carbon in intimate contact with the materials under treatment is possible; a state of things scarcely, if ever, attained in practice, and consequently the loss due to incomplete combustion, and other causes, frequently more than neutralises any theoretical gain over gaseous fuel. The ease with which perfect combustion of a gas can be obtained by regulating the supply of gas and air, the readiness with which it can be conducted to any required point, superheated or burnt under pressure, made to give an oxidising or a reducing flame at pleasure, and the general control that can be exercised over the size and temperature of the flame, in most cases more than compensate for the smaller number of heat units evolved as compared with solid Carbon. A certain amount of energy has thus to be sacrificed in order to gain in convenience, and to carry out certain operations which can only be done efficiently with gaseous fuel. The necessity for superheating the fuel and for keeping solid fuel out of contact with the bath of metal, makes gaseous fuel a *sine qua non* in the case of the open hearth furnace, and until Siemens solved the problem of cheap gasification of coal, this process of steel making was impossible.

Description of Producer.—The ordinary gas producer is a fire-brick lined receptacle in which air and steam are drawn or forced through a bed of incandescent fuel, the essential condition being to provide a sufficiently deep layer of incandescent fuel to insure that any Carbon Dioxide formed is, as far as possible, converted into Carbon Monoxide (CO) before it leaves the producer, and that the water vapour introduced is split up with the formation of Hydrogen and Carbon Monoxide. The resulting gas will

contain Carbon Monoxide, mixed with some Hydrogen and small quantities of olefiant gas, marsh gas, and Carbon Dioxide gas, and about 60 per cent. Nitrogen, which latter must always be present so long as we use air for the combustion of the Carbon.

Chemical Reactions in the Producer.—When coal is distilled in a closed retort only a small proportion is converted into gas—chiefly volatile Hydrocarbons—the greater part being left as coke. The object of the producer is to convert the whole of the Carbon in the coal into combustible gas so that nothing but ash is left, and this may be done by drawing air through a fairly thick bed of incandescent Carbon, the Carbon uniting with the Oxygen of the air to form Carbon Monoxide. Although the final result is Carbon Monoxide, the commonly-accepted view has been that Carbon burns directly to Carbon Dioxide, thus—

Carbon + Air = Carbon Dioxide.

$$C + O_2 + N_x = CO_2 + N_x,$$

and that this CO_2, in traversing a bed of red-hot Carbon, reacts with another atom of Carbon to form Carbon Monoxide, thus—

Carbon Dioxide + Incandescent Carbon = Carbon Monoxide.

$$CO_2 + C = 2\,CO.$$

In view, however, of Mr. H. B. Baker's work * on the combustion of solid Carbon, and the work of Professor Dixon † on the rates of explosion of Cyanogen and Oxygen, it is very probable that solid Carbon burns directly to Carbon Monoxide, thus—

Carbon + Air = Carbon Monoxide.

$$C + O + N_x = CO + N_x,$$

and that Carbon Dioxide is only formed by a secondary combustion of this Carbon Monoxide. Whichever of the above views be adopted will make no difference to the thermo-chemical result obtained. Of the total heat available on the combustion of Carbon to Carbon Dioxide, 8,080 heat units for every unit of Carbon burnt, 2,450 will be developed in the producer itself by the formation of Carbon Monoxide, and the remaining 5,630 heat units will be available for the production of heat in the Siemens furnace or elsewhere when the CO is burnt to CO_2. As the air contains 79 per cent. of Nitrogen, which takes no part in the reaction, the resulting gas will be largely diluted with this, and a gas of the following percentage composition should, theoretically, be obtained:—

Carbon Monoxide, ...	34·7 per cent.
Nitrogen, ...	65·3 ,,

but, as will be seen later on, this is never obtained in practice.

Again, when steam is passed through a bed of incandescent Carbon, the water vapour is split up with the production of a gas containing equal volumes of Hydrogen and Carbon Monoxide, thus—

$$H_2O + C = H_2 + CO.$$

The decomposition of the water vapour, however, is attended with an absorption of heat which is greater than that given out by the combustion of the Carbon to Carbon Monoxide, so that the final result of this reaction is loss of heat, and a rapid cooling down of the incandescent fuel, when the reaction ceases. It is obvious, therefore, that the heat of the fuel cannot be maintained by water vapour alone, and what is usually done is to inject a

* *Journ. Chem. Soc.*, 1885, vol. xlv., p. 349; also, *Phil. Trans.*, 1888, vol. clxxix. A, p. 571.
† *Journ. Chem. Soc.* (*Trans.*), 1896, vol. lxix., pp. 759, 774; also, 1899, vol. lxxv., p. 630.

mixture of air and steam together, so that the heat developed by the direct combustion of the Carbon by the Oxygen of the air more than compensates for the heat absorbed by the splitting up of the water vapour. The larger the amount of steam we can inject, subject to its being split up, the larger will be the percentage of combustible gases obtained, as the Nitrogen introduced with a smaller quantity of air will be less. We have thus to maintain a balance between the combustion of Carbon to CO, which produces heat, and the decomposition of steam, a reaction which absorbs heat; therefore the amount of air and steam admitted must always be so regulated that the heat produced shall be considerably in excess of that absorbed.

Theoretically, it is possible, starting with Carbon in a state of incandescence, to introduce sufficient steam (one of steam to five of air by weight) for the Oxygen from it to combine with half the Carbon, and thus to produce one-half the Carbon Monoxide in any given time, the other half of the Carbon being burnt by Oxygen from the air. The heat units evolved would then about balance each other, but practically so much heat is lost by radiation, and carried off from the producer by the gases and ashes as sensible heat, that only half this amount of steam can be used, and in practice it should never exceed $\frac{1}{12}$ of the weight of air introduced. Other things being equal, the amount of water vapour which can be admitted will depend greatly upon the depth of the bed of fuel which can be maintained in a state of incandescence. The depth of fuel which is found to give satisfactory results varies with the height of the producer and the quality of the fuel used; in steel works' producers this is about 5 feet, as, if deeper than this, it is impossible to keep it sufficiently well stirred to prevent clinkering, which leads to the formation of air channels and to irregular and incomplete combustion in different parts of the bed. As a matter of fact a comparatively small amount of steam is decomposed in the ordinary producer, the chief function of the steam injection being to cool the bed of fuel, lower the temperature, and thus prevent clinkering. In the case of some special producers, where precautions are taken to condense any undecomposed steam escaping with the gases, very much larger quantities can be employed. For many years, both in Siemens and in other producers, it has been the practice to inject steam under pressure, which enables the quantity to be better controlled, according as the producer is working hot or cold, than when relying upon evaporation from a trough under the grate as in the original Siemens. The pressure of the steam can also be used to inject air, and to maintain an outward pressure in the mains.

The heating value of the gas depends not only upon the ultimate number of heat units developed, but upon the intensity or temperature of the flame, and this will vary, for the same gas, with the conditions under which it is burnt. For example, Hydrogen when burnt in air gives a very much lower *temperature* than when burnt in Oxygen, although the total number of heat units developed is the same in each case; but when air is employed, for every part of Oxygen used there are 3·35 parts of Nitrogen, which have to be heated up at the expense of the flame, with consequent reduction of temperature. Again, assuming the combustible gas is not pure, but contains any appreciable quantity of Nitrogen or other inert gas, this obviously reduces its effective heating power, and it is consequently of the greatest importance to so regulate the production that the gas shall contain the maximum percentage of combustible gases. If we were able to draw Oxygen instead of air into our producer the calorific efficiency of the gas produced would be enormously increased, but as this is impossible we try to increase

the relative percentage of combustible gases by the injection of as large a quantity of steam as is possible without unduly cooling the producer.

As the fuel is charged in at the top, this part of the producer is always comparatively cool, and here the volatile products are driven off, whilst the **CO** is formed and steam is split up in the lower zone.

Producers may be divided into two main classes :—

(1) **Those worked with natural draught.**

(2) **Those worked with forced draught.**

And these may be again subdivided into—

Producers with firebar bottoms.
Producers with solid bottoms.
Producers with water bottoms.

The Siemens Producer.—The original Siemens producer, as introduced by the late Sir William Siemens and his brother in 1861-62, was an open producer, the fuel resting on firebars, and as it is the parent of all modern producers the following description is taken verbatim from a pamphlet published by Messrs. C. W. & F. Siemens, in 1862, and reprinted in the *Iron and Coal Trades Review* of March 4th, 1898.

"The producer is shown in fig. 88, and is a chamber lined with fire-bricks, into which fuel is introduced at intervals through the covered holes, A, and descends gradually on the inclined plane, B, which is set at an inclination of from 45° to 60°, according to the nature of the fuel used. The upper portion of the incline, B, is made solid, being formed of iron plates covered with fire-brick, but the lower portion, C, is an open grate formed of flat horizontal steps. At the foot of the grate, C, is a covered water trough, D, filled with water up to a constant level from the small feeding cistern, E. The large opening under the water trough is convenient for drawing out clinkers, which generally collect at that point. The small stoppered holes, F and G, at the top of the producer are provided to allow of putting in an iron bar occasionally, to break up the mass of fuel and detach clinkers from the side walls. Each producer is capable of converting daily about two tons of fuel into gas.

"The action of the gas producer in working is as follows :—The fuel, descending slowly on the solid portion, B, of the inclined plane, becomes heated, and parts with its volatile constituents. There now remains from 60 to 70 per cent. of purely carbonaceous matter to be disposed of, which is accomplished by the slow current of air entering through the grate, C. For every cubic foot of combustible Carbon Monoxide thus produced, taking the atmosphere to consist of one-fifth part by volume of Oxygen and four-fifths of Nitrogen, 2 cubic feet of incombustible Nitrogen pass also through the grate. Not all the carbonaceous portion of the fuel is, however, volatilised on such disadvantageous terms, for the water trough, D, at the foot of the grate emits steam through the small holes, I, under the lid, and each cubic foot of steam, in traversing the layer of from 2 to 3 feet of incandescent fuel, is decomposed into a mixture consisting of 1 cubic foot of Hydrogen and nearly an equal volume of Carbon Monoxide, with a variable small proportion of Carbon Dioxide. . . . The opening, H, leading from each producer into the main gas flue can be closed by inserting a damper from above, in case any one of the producers is required to be stopped for repairs.

"It is important that the main gas flue leading to the furnaces should contain an excess of pressure, however slight, above the atmosphere, in order to prevent inward draughts of air, which would produce a partial

combustion of the gas. It is therefore necessary to deliver the gas into the furnace without depending upon a chimney draught for that purpose. This could easily be accomplished if the producers were placed at a lower level than the furnaces; but as that is generally impossible, the following plan has been adopted. The initial heat of the gas, which must in any case be sacrificed, is therefore made available for producing a plenum of pressure by making the gas rise about 20 feet above the producers, then carrying it horizontally 20 to 30 feet through the wrought iron tube, J, and letting it again descend to the furnace. The horizontal tube, J, being exposed to the atmosphere causes the temperature of the gas to drop, from 100° to 150°, which increases its density from 15 to 20 per cent., and gives a preponderating weight to that extent into the descending column, urging it forward into the furnace."

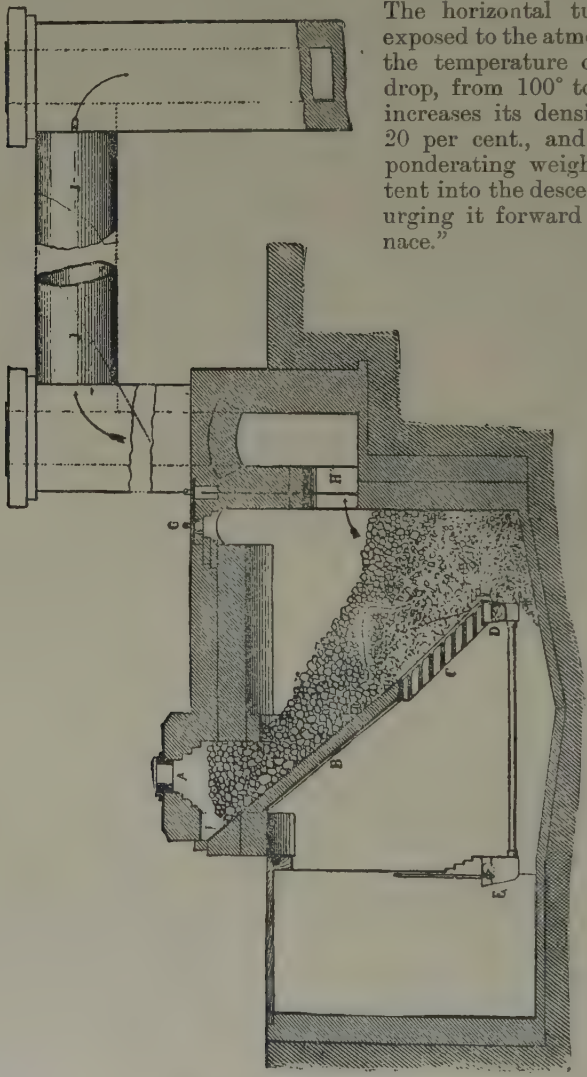


Fig. 88.—Siemens Producer, 1862.

In this producer we have all the essentials for the production of a highly combustible gas, and it is interesting to note the ingenious device to maintain an outward pressure in the gas flues by using some of the sensible heat

of the gas to do the work direct instead of employing mechanical means to force the gases into the furnace.

By lowering the temperature of the gases in the cooling tube their density is increased, and, consequently, they sink in the down-comer tube, which acts as a syphon, and enables an internal pressure equal to $\frac{1}{10}$ to $\frac{2}{10}$ of an inch of water above the atmospheric pressure to be maintained.

Modern Producers.—The following sketches illustrate various forms of modern producers, which differ from each other in detail, but are all capable of giving excellent results with good fuel:—

The Siemens Producer (*Modern Type*), fig. 89.—This is one of the best-known types of grate producer. D is the hopper by which the fuel is introduced into the rectangular chamber C, with firebars shown at F. The ashpit is closed by hinged doors in front, but air is injected with a steam jet, A, through two openings on each side, shown at B. The ashpit is cooled by water in an iron tray, the water being kept at practically a constant level, and the gases are drawn off at the top of the producer, and pass through the gas flue, E, on their way to the furnace.

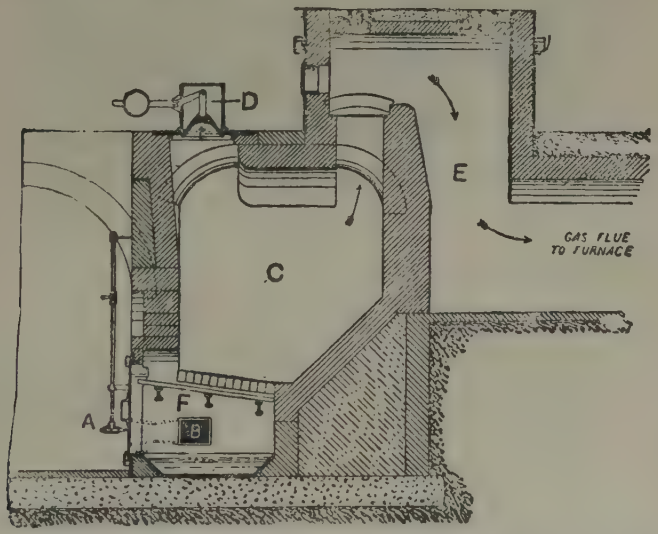


Fig. 89.—Modern Siemens Producer—A, Steam injector; B, opening through which steam injected; C, body of producer; D, charging hopper; E, gas flue.

Wilson Producer.—This producer (fig. 90) may be taken as the representative of solid bottom producers, the fuel resting on the bottom, and air and steam being injected through a central passage known as the distributer, supported by a fire-brick arch communicating with the body of the producer. The fuel is charged through a central hopper, CH, at the top, and the gas is drawn off through a series of openings, *a*, *a*, *a*, arranged symmetrically round the circumference of the producer to the downcomer, B. The producers are cylindrical, and vary from 8 to 12 feet in diameter, and gasify on an average from 25 to 30 lbs. of coal per square foot of bottom area per hour, although higher results can be obtained. To remove the ashes the producer has to be stopped at regular intervals, and iron bars are pushed through small openings and allowed to rest on the central fire-brick

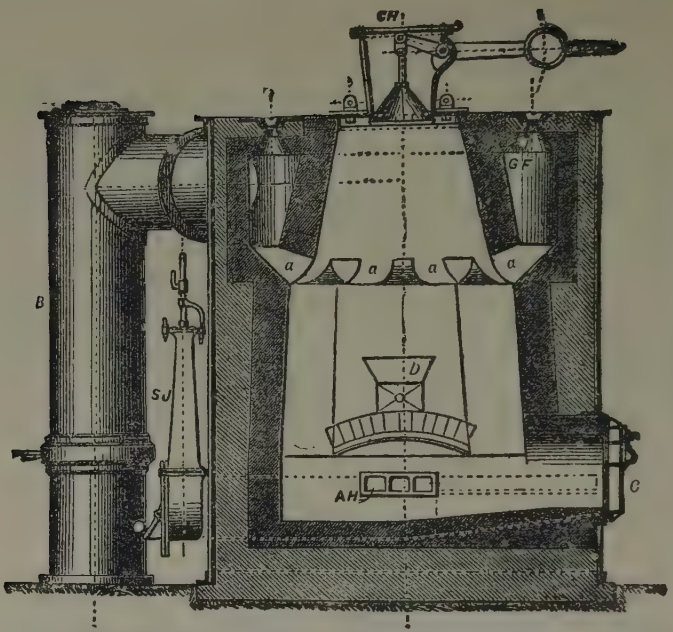


Fig. 90.—The Wilson Producer—*a*, *a*, *a*, Openings round circumference of producer through which gas is withdrawn; B, downcomer or gas flue; C, door for raking out ashes; D, air distributer.

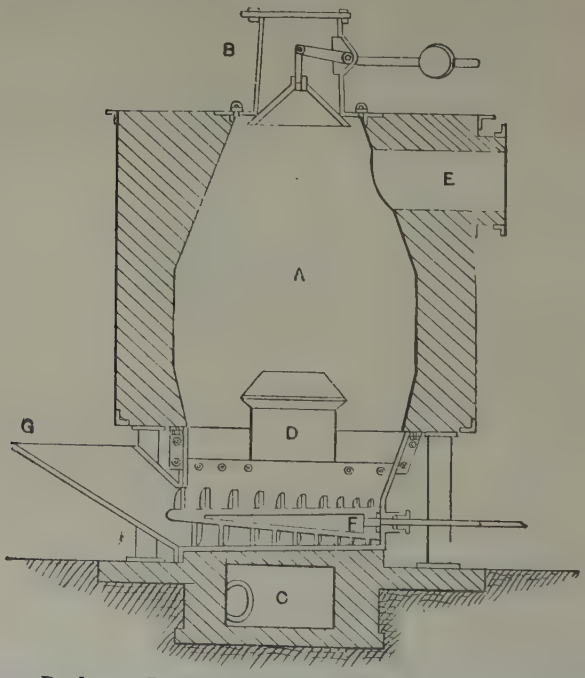


Fig. 91.—Wilson Producer—B, Charging hopper; C, air flue; D, air distributer; E, gas flue to furnace; F, screw for removing ashes; G, ash-pan filled with water.

arch to support the fuel. The cleaning doors, C, are opened and the ashes raked out. The bars are then withdrawn, the charge allowed to sink, and the blast turned on.

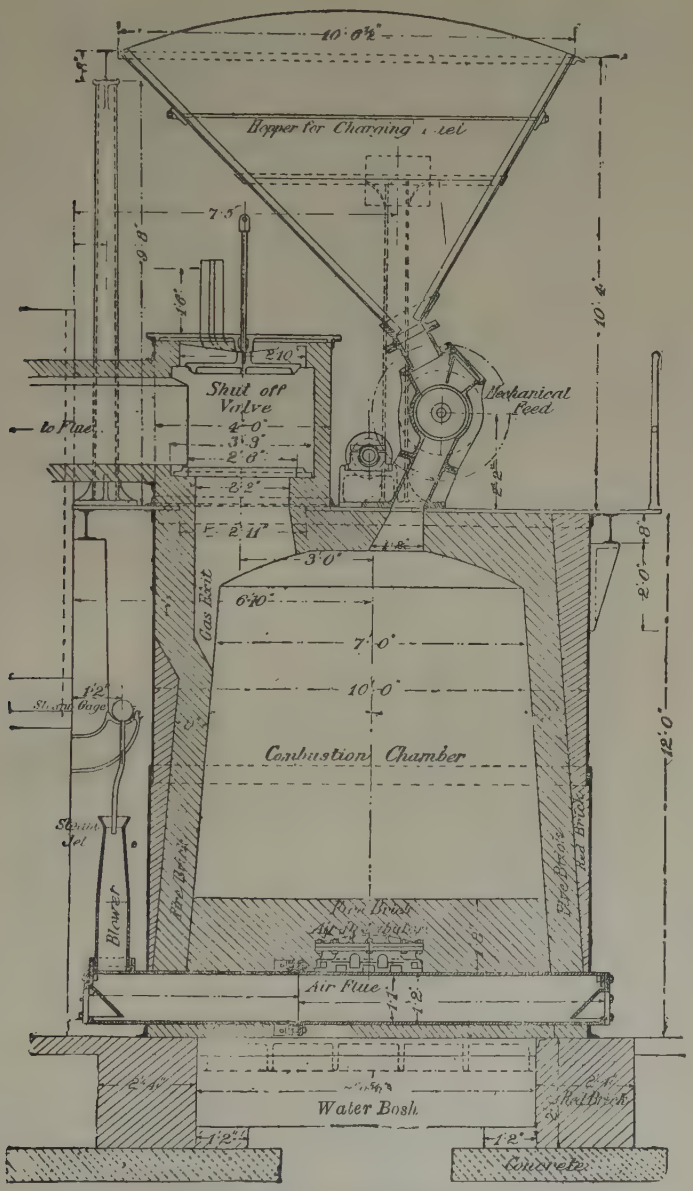


Fig. 92.—Wilson Gas Producer.

In a later design the ashes are removed by an Archimedean screw without stopping the producer, and this is shown in fig. 91.

This producer is charged and the gas drawn off as in the solid bottom producer, but the ashes and clinker are continuously forced out of the ash-pan, G, by the revolving screw, F, which rotates under water. This producer is therefore practically a water-bottom producer, as the water in G acts as a seal. The air is injected by a steam jet in the usual way.

In figs. 92 and 93 are sketches with leading dimensions of a large Wilson producer, fitted with mechanical feed and water bottom, the air distributer and other details being the same as in the closed bottom producers. The

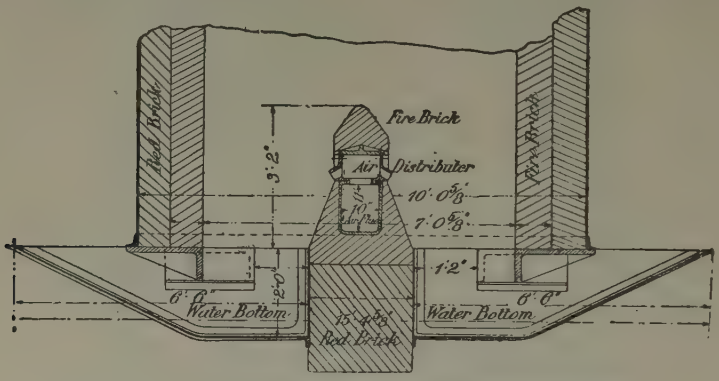


Fig. 93.—Section through Air Distributer and Water Bottom.

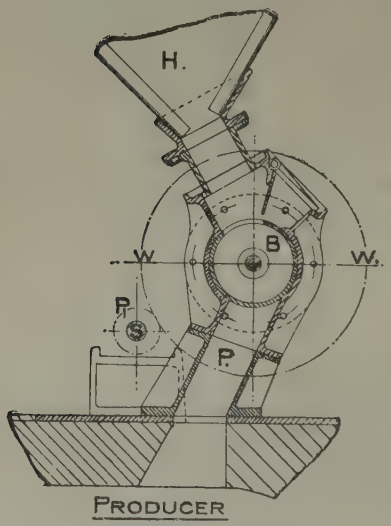
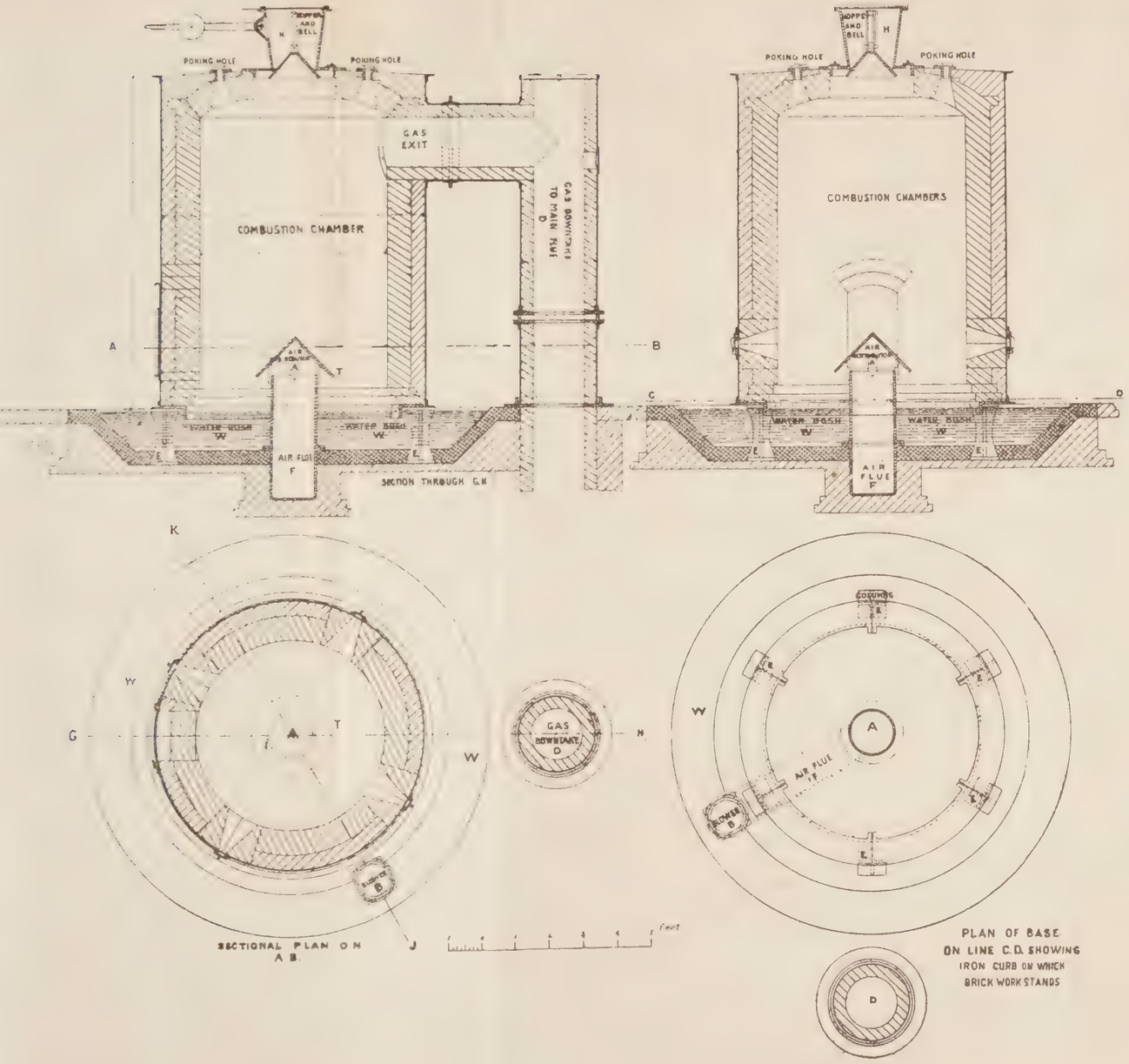


Fig. 94.—Mechanical Feed for Producer.

H, Hopper containing fuel which falls into the revolving barrel, B, through the opening shown. The barrel revolves until the opening is over the passage, P, when the fuel falls into the producer. The barrel is driven by shaft, S, on which spur pinion, P_1, is fixed, this latter gearing into W, which is keyed on the same shaft as the barrel.

mechanical feed is an important addition, as if carefully supervised, besides the saving in labour over hand-charging, the fuel is fed more regularly and can be better distributed over the producer. It is customary to have some form of mechanical feed now in all modern installations of producers, and that in the figure consists of a revolving barrel into which the fuel from the hopper falls when an opening in it comes underneath the bottom of the hopper. The barrel then revolves until the opening comes opposite t'

PLATE V.—The Dawson Gas Producer.



Figs. 95 and 96.

Figs. 97 and 98.

Figs. 99 and 100.

To face page 121.]

PLATE VI.—"Duff" Gas Producer, as used for Ammonia Recovery.

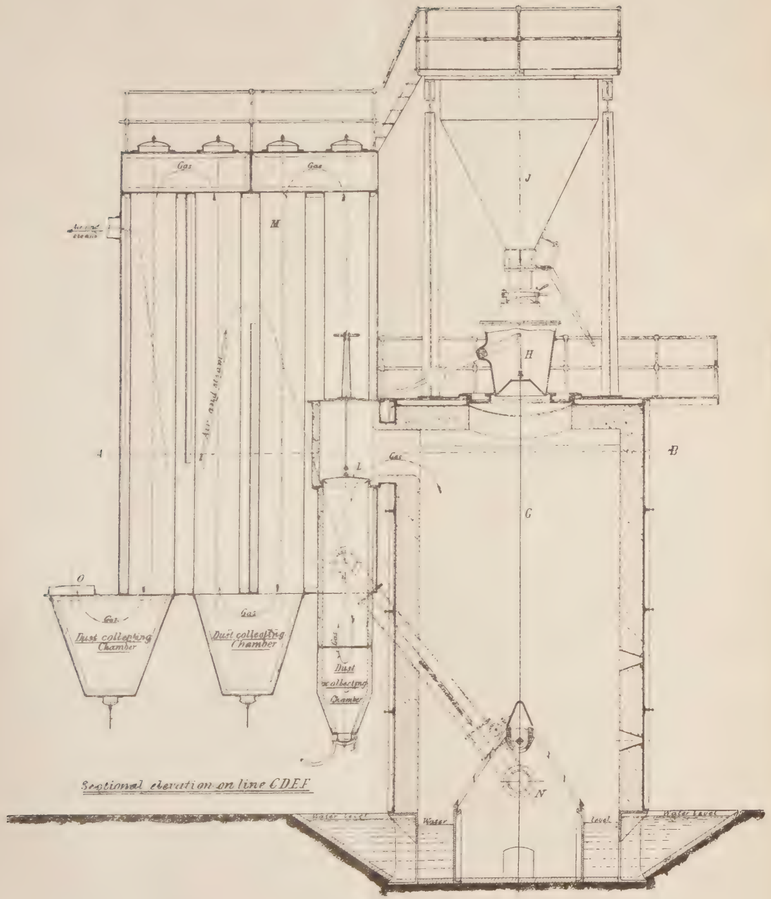


Fig. 101.

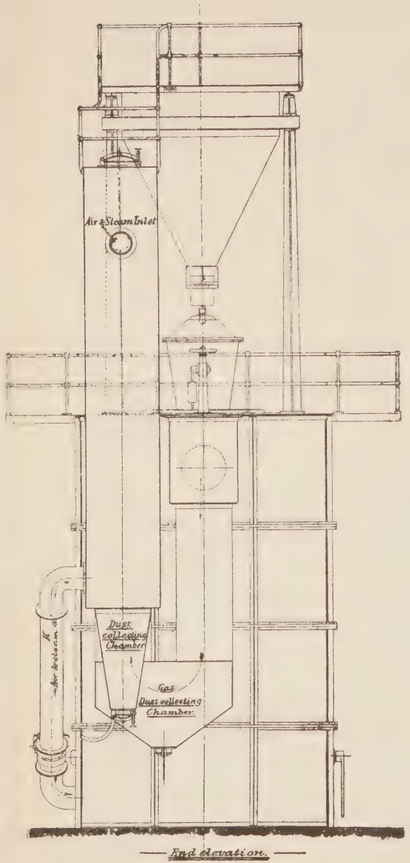


Fig. 102.

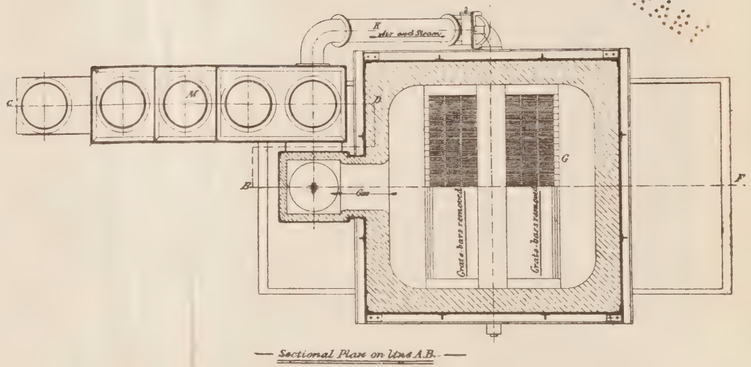


Fig. 103.

Plan, front elevation, and end view (figs. 101, 102, and 103) illustrate the general design of the "Duff" Gas Producer as arranged to work on ammonia recovery plant.

The coal is elevated on to the hopper platform and shot into the hopper, J, from which it is discharged into the gas-tight charging hopper, H, from which it is dropped into the producer chamber, G.

A mixture of superheated air and steam is blown through the superheater, M, and the pipe, K, to underneath the gratings, N, through which it is distributed over the base of the fuel bed.

The gas escaping from the top of the fuel bed issues through the valve, L, then through the dust collecting chambers and pipes of the superheater, M, alternately, issuing at O to the collecting main leading to the ammonia recovery plant.

A shaking arrangement is provided for shaking the dust out of the distributing grids at the base of the producer, and suitable operating mechanism is provided at the top of the producer for shooting in the coal and trapping the gas, while at the base of the producer means are provided for collecting and drawing off the dust. The ashes are removed through water-sealed troughs at the base of the producer.

charging hole in the producer, when the fuel is discharged into the producer. As the barrel revolves it takes up another charge of coal from the hopper, and again deposits it in the producer. This arrangement has given very satisfactory results at the works of the Steel Company of Scotland, where it has been in use for some time.

The Dawson Producer (figs. 95 to 100, Plate v.).—This is a water-bottom producer, and is an excellent representative of the type. Here the ashes fall into a trough of water at the bottom of the producer, from which they can be drawn from time to time, the water acting as a seal to prevent the escape of gas. The shell, which is a cylindrical iron casing, is lined with fire-brick, and rests on short columns, E, E, E, in the water trough, the air and steam being injected through a centre pipe, F, which is covered with a conical cap, A, with small air spaces for the air and steam to pass into the body of the producer. The gas is drawn off at the top through the opening marked "gas exit," on one side of the producer, and passed through the short horizontal flue to the downtake. In starting the producer it is usual to fill it above the water level with ashes, and then light the fire and charge the fuel in the usual way.

The advantages of the water-bottom producer, which is the type of producer now in very general use, are that practically all heat from the ashes is utilised by converting the water into steam, and the ashes can be readily withdrawn and are cool enough to be easily removed. On the other hand, water bottoms are liable to increase the percentage of Sulphur in the gas, and for this reason they have in some works been discontinued, solid bottoms being substituted.

The Duff Producer (figs. 101 to 103, Plate vi.).—This is another form of producer which is being largely used in this country, especially in connection with Ammonia recovery plants. One special feature about it is that the steam and air are superheated by the gas which comes from the producer, the gas being thus partially cooled before being taken to the Ammonia recovery plant. By thus utilising the sensible heat of the producer gases to heat up the air and steam before they are forced into the producer, an additional number of heat units is introduced, which enables a greater quantity of steam to be injected into the producer without cooling it down below a fair working temperature. Particulars of the general arrangement will be readily understood from the figures (Plate vi.), to which a description is attached. The producer can, of course, be used either with or without Ammonia recovery plant.

The Mond Producer.—When the tarry matters resulting from the distillation of coal are passed through a bed of incandescent fuel, they are converted entirely into gases; many attempts have been made to do this, and at the same time to recover the Nitrogen present in the fuel in the form of Ammonia, but only with partial success. In the latest form of Mond producer they have not only succeeded in destroying the greater part of the tar resulting from distillation, but also in recovering something like 90 lbs. of Sulphate of Ammonia per ton of coal gasified, which is equivalent to a recovery of about 70 per cent. of the Nitrogen originally in the fuel.

This is largely effected by injecting into the producer very large quantities of steam—about $2\frac{1}{2}$ tons for every ton of coal used—thus maintaining a much lower temperature in the producer than is usual, so that the resultant Ammonia is not decomposed, the fuel cakes only slightly, and only a little clinker is formed.

The greater portion of this steam passes out of the producer undecom-

posed, but during its condensation its sensible and latent heat are utilised to produce fresh steam for use in the producer. The gas containing the Ammonia is passed through an absorbing apparatus. The fuel is mechanically fed into the producer, and is charged in large quantities of 8 cwts. to 10 cwts. at a time, and the ashes are withdrawn without interfering with the regular continuous working. The gas generated is uniform in quality, and, as no tar is produced, the plant can be kept clean, and the gas cooled to any desired extent, without blocking the pipes and valves.

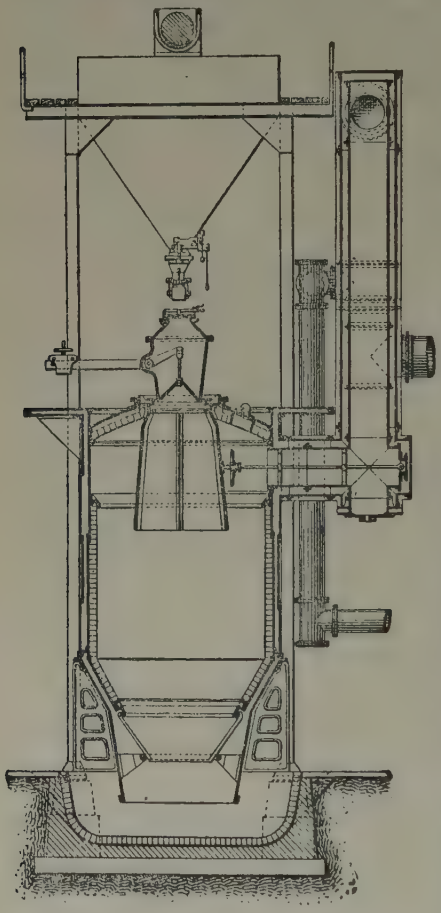


Fig. 104.—Mond Gas Producer.

The gas produced is very high in Carbonic Acid, but this is to a great extent compensated for by the large percentage of Hydrogen, and the calorific value appears to be quite equal to ordinary producer gas.

The following are average analyses :—

	Per cent.	Per cent.
Hydrogen (H), . .	24·8*	27·5†
Marsh Gas (CH_4), .	2·3	2·0
Carbon Monoxide (CO),	13·2	11 0
Nitrogen (N), . .	46·8	43·0
Carbon Dioxide (CO_2), .	12·9	16·5

The question how far such a gas is capable of yielding the high temperature necessary for steel making may, in the opinion of some steel makers be open to doubt; but, from the experiments of Mr. Darby,‡ there seems reason to believe that, provided the gas is heated to a high temperature by the usual system of regeneration, it will give good results, notwithstanding the large percentage of incombustible gases present.

Against the recovery of the Ammonia in this producer must be set the cost of raising the large quantity of steam required; but when full allowance is made for this, there is still a very substantial balance left. The reason why the producer has not been more largely adopted in steelworks' practice is probably mainly due to the considerable cost of the plant as compared with an ordinary producer plant of the same capacity. A few years ago a large company was formed to manufacture the gas and distribute it through mains to various works within a definite area, and there is no question that a gas suitable in all respects for many metallurgical and manufacturing operations can be produced and distributed at a comparatively low price.

* *Min. Proceed. Civil Engineers*, vol. cxxix., p. 210.
† *Iron and Steel Inst. Journ.*, 1896, vol. i., p. 144. ‡ *Idem.*

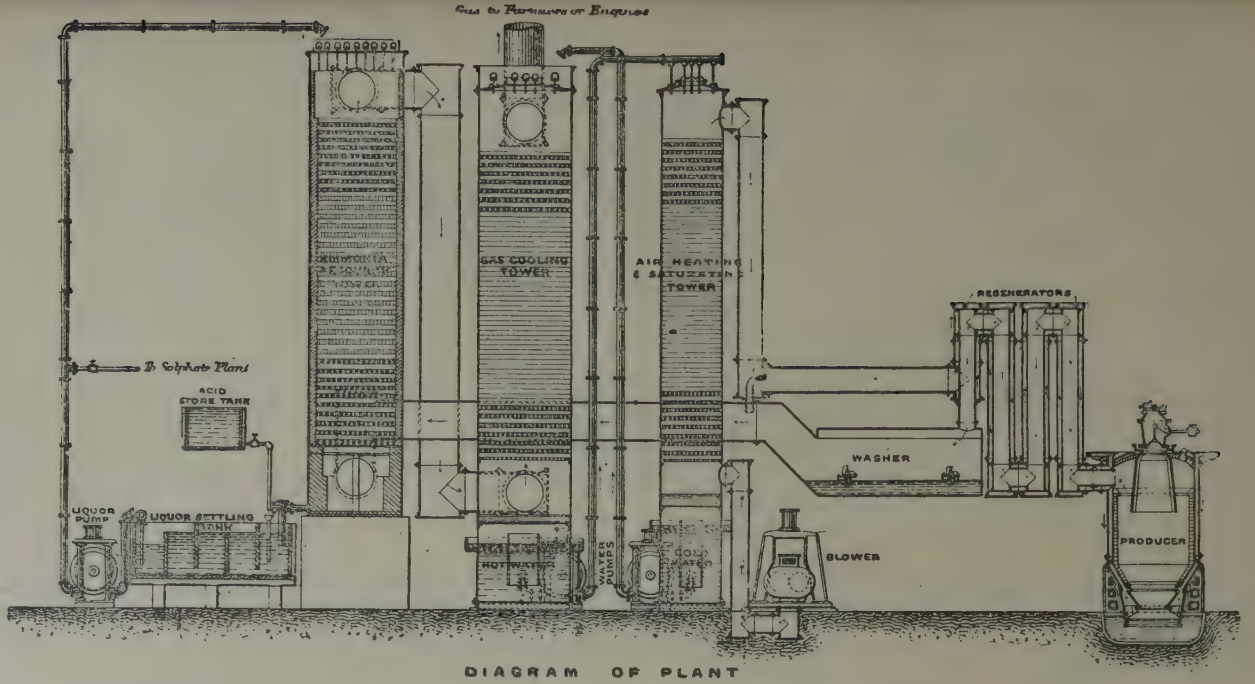


Fig. 105.—Mond Producer and Ammonia Recovery Plant.

The hot gas leaving the producer passes into the regenerators, consisting of a series of wrought-iron vertical double tubes, so arranged that, while the hot gas is being cooled by passing in one direction through the inner tubes, the air and steam are being heated by passing in the opposite direction through the annular space between the tubes. The gas then passes into the long chamber called a washer, which is kept completely filled with fine spray by revolving dashers which just skim the surface of the water. By this intimate mixture of gas and water spray, the temperature of the gas is reduced to about 90° C. The gas then passes to the Ammonia recovery tower on the left, as shown by the arrows, and meets a descending stream of Sulphuric Acid, which deprives it of its Ammonia, and finally it passes into the cooling tower, which is filled with wood packing, to give a large surface where it meets a downward current of cold water, when a great portion of the steam it contains is condensed. It is then taken direct to the furnace for use. The hot water from the gas cooling tower is pumped into the air heating tower on the right-hand side of the diagram, where it gives up its heat and saturates the cold air with steam passing through it on its way to the producer. Throughout the process the gas is under pressure.

In works where large quantities of gas are required, the cost of production at the works would be too low for any outside plant handicapped with the extra cost of distribution to compete; but in the case of comparatively small consumers, especially if there are a large number within a small radius, a large central plant may be able to meet their requirements and supply gas on more advantageous terms than they could produce it in small quantities themselves.

Fig. 104 is a sketch of the producer. It consists of an inner and outer wrought-iron cylindrical shell, the latter lined with fire-brick for a portion of its height, the top is arched, and is lined with fire-brick, while the bottom portion is an inverted truncated cone. The whole producer is supported by cast-iron brackets, and a water bosh at the bottom forms a seal.

The fuel is delivered direct from the railway wagons into a large hopper over the producers, and it is charged into the hoppers of the different producers by a creeper. When the hopper is filled with slack, the hood valve which closes the bottom is opened, and the fuel falls into the bell-shaped casting suspended from the top of the inside of the producer. This internal bell being surrounded by the hot producer gas, the slack undergoes partial distillation, and as these products of distillation have necessarily to pass downwards through some of the hot fuel before they can escape, the tar is practically all destroyed and converted into gas.

At the bottom of the producer are two cast-iron rings, on which sloping bars are fixed, but as these do not reach the centre, part of the weight of the superincumbent fuel rests upon the ashes, which form a reversed cone, filling the centre space down into the water. The ashes are withdrawn from the water bosh in the usual way. The general arrangement of the producer, with its Ammonia recovery plant, is shown in fig. 105.

Mechanical Producers.—Many attempts have been made from time to time to devise methods for mechanically stoking producers, with the object of saving labour, insuring the more regular production of gas by breaking up the clinker, and stirring the fire more completely than can be done by hand-stoking. The solution of the problem has been, however, surrounded with great difficulties; the impossibility of devising any metal stirrer to work at the temperature inside the producer without becoming rapidly distorted or burnt away seeming insurmountable. The essential conditions for success are:—1. That the mechanical appliance must stir the whole of the producer, break up clinker, and prevent air passages being formed. 2. That it must be able to withstand the abrading action of the fuel and clinker at the high temperature of the producer. 3. That, in the event of its meeting with any obstruction, such as a large mass of clinkers, which it is unable to break up, it must neither stop working, nor bend nor break. The Talbot, Hughes, Kerpely, and Rehmann producers now working successfully in America, on the Continent, and in this country, apparently fulfil most of the above conditions, and are gradually being introduced into various works.

The Talbot Producer.—This producer (fig. 106) is designed with a stirrer consisting of a vertical shaft carrying two radial arms, and having both a vertical and a rotatory movement.

The stirrer is water-cooled by a flexible copper tube, carrying water in a constant stream to both ends of the radial arms, and this stream finds an exit at the top of the shaft into a pan, from which it is conveyed away.

The mechanical poking is effected by the slow rotary and up-and-down motion of the stirrer, the vertical shaft being carried up through the cast-iron

top of the producer, supported by a suitable bearing, and extending upwards to the platform resting on the top of the main structure. Its upper end is connected with a crank shaft on the upper platform, by which it receives

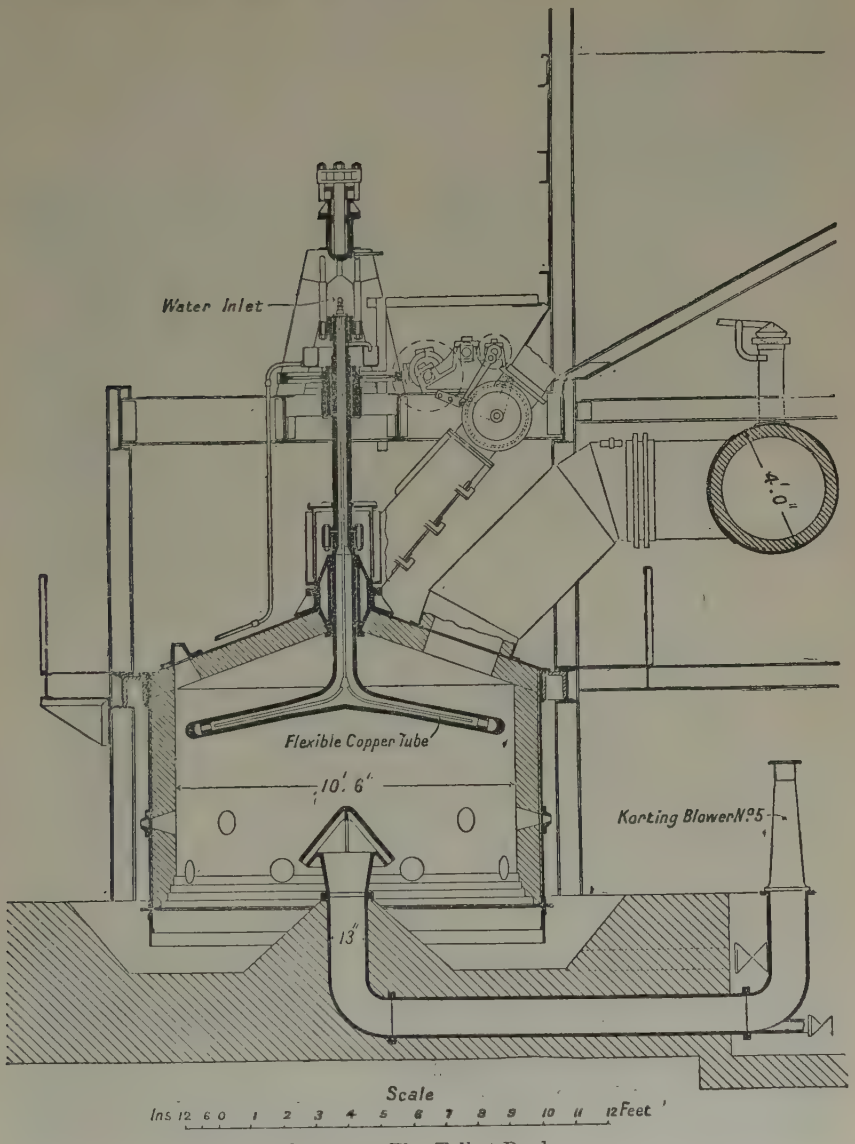


Fig. 106.—The Talbot Producer.

a vertical and reciprocating motion. The crank is driven through suitable gearings at a uniform speed by an electric motor, which also performs the rotary driving of the vertical shaft. The rotary action of the stirrer tends to prevent the formation of clinker, or to break it up as formed, but should

the radial arms come into contact with any solid obstruction, the gear is relieved from liability to break down by a cam which gives way. The electric motor recommended for driving the mechanical poker is of 10 H.P., wound for a direct current of 220 volts, and fitted with a controller for regulating

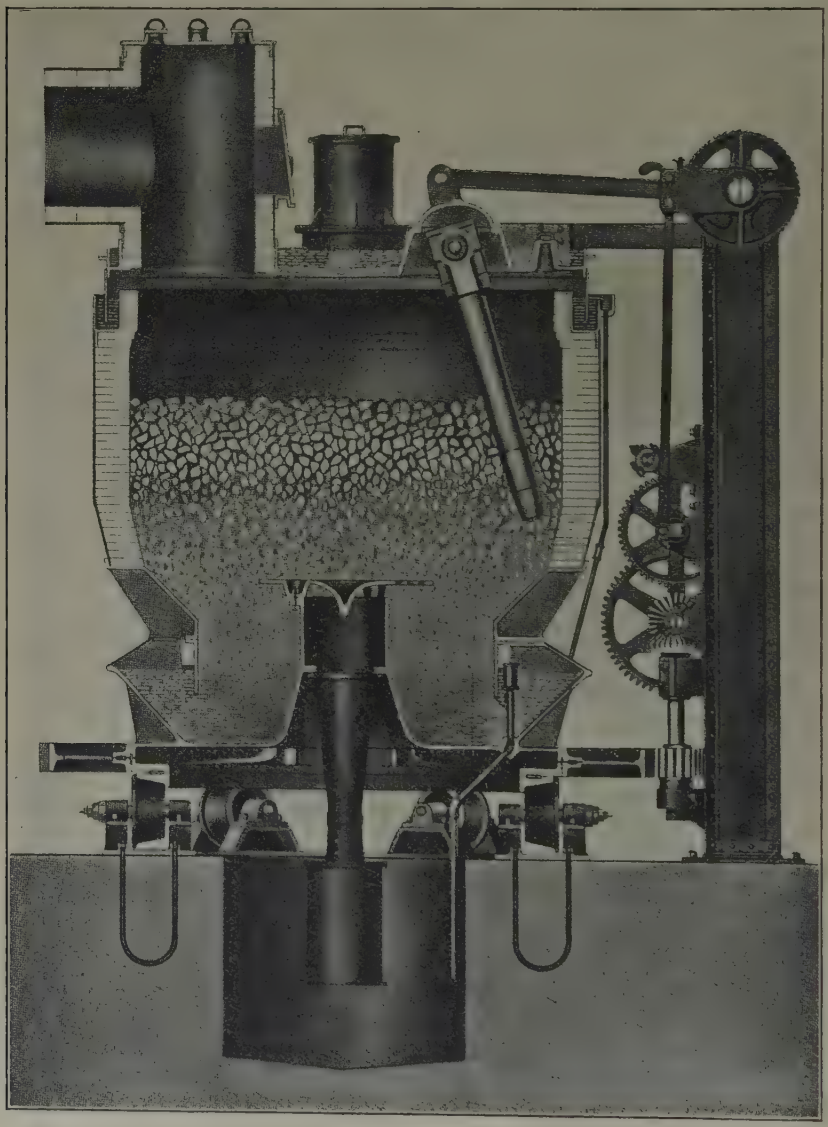


Fig. 107.—The Hughes Producer.

the speed. The motor is of the enclosed type, specially designed for severe and continuous service.

The producer shown in fig. 106 gasifies 1 ton of coal per hour, works

well, and the gas produced contains from 4 to 5 per cent. of CO_2, 26 to 28 per cent. of CO, 13 to 14 per cent. of Hydrogen, and 3 to 4 per cent. of Hydrocarbons.

The Hughes Producer.—In this producer (fig. 107) the body of the producer is mounted on a turn-table which is slowly revolved. A hollow water-cooled poker suspended from a trunnion independent of the shell of the producer, as shown in the sketch figure, is moved backwards and forwards by means of a ratchet gearing actuated by a crank and crank shaft driven by any suitable means. This mechanism moves the poker backwards and forwards from centre to circumference of the producer, which action, combined with the revolution of the body of the producer, stirs and breaks up the mass of the fuel through the whole producer, and evenly distributes it.

The producer shell is of steel plate, and is secured to a cast-iron base ring, to which is bolted a cast-iron water-seal, forming an ash receptacle. The base ring rests upon supporting columns bolted to a cast-iron revolving turn-table. This turn-table has at its outer circumference a cast-iron rack, into which meshes a spur pinion keyed to a vertical shaft and connected to the main driving shaft by a train of gearing; thus the turn-table is rotated, and with it the body of the producer and the ash pan. The bottom of the turn-table is fitted with a steel tread resting on six conical chilled-iron carrying wheels, and supported by the necessary axles and boxes. As the producer shell revolves, the ashes work down and are deposited in the water-sealed ash pan, from which they may be shovelled direct to car without the intervention of machinery.

The producer top is a steel casting flanged and ribbed to provide for water-cooling, a water-seal being formed by a top flange at the outer circumference of the producer cover. The use of a steel casting for this top adds materially to its durability, for experience has demonstrated that where the parts are exposed to heat, steel castings are superior to cast iron.

Each producer is equipped with two feed hoppers fitted with counterbalanced bells and gas-tight swing covers, placed at unequal distances from the vertical axis of the producer, so that the coal is deposited in concentric rings as the producer shell rotates, thus giving a proper distribution of coal. A gas outlet provided with a cleaning door, peep holes, etc., is attached to the top of the producer cover. This outlet has a short flanged neck, to which a connection from the gas outlet to the gas flue may be made. The power required to operate a producer is about 3 electric H.P., and the standard size producer, which is 10 feet diameter inside the brick lining, is capable of gasifying 1 ton of good coal per hour. This producer is largely used in America, and is said to give excellent results.

The average composition of the producer gas is approximately CO_2 4 per cent., CO 26 per cent., Hydrocarbons 3 to 4 per cent., Hydrogen 13 per cent., Nitrogen 53 per cent.

The Kerpely Producer.—This producer is illustrated in fig. 108, and the special features are the water-cooled bottom section and the continuous but slowly revolving grate, which, as it rotates, crushes the slag or clinker against the walls, and prevents its sticking to the lower part of the walls of the producer. The revolving grate, originally rhombic in shape, is now made circular, but placed eccentrically to the centre line or vertical axis of the producer, and it revolves with the water-cooled ash pan once in three hours. The grate is built up of a number of stepped plates, with

spaces for air to pass between them, so that the air is distributed evenly over the whole producer. The ashes are removed mechanically by a fixed shovel in the ash pit, the height of which is adjustable.

The Rehmann Producer.—This is a modification of the Kerpely producer, the principal difference being in the construction of the grate, which consists of cones supplied with openings (fig. 109). The fuel bed is loosened at the points of the cones above the grate, and slides downwards along these

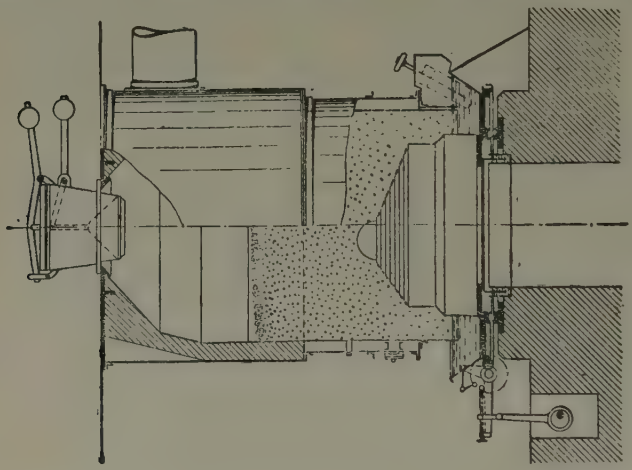


Fig. 108.—The Kerpely Producer.

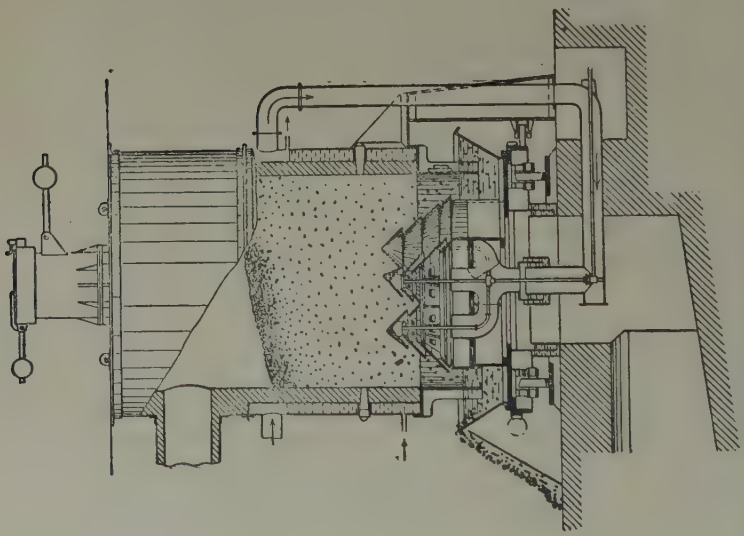


Fig. 109.—The Rehmann Producer.

cones. In the cones are openings for the air supply, but these are covered so that they do not choke as the grate revolves, and air is conveyed to each cone by a separate pipe, and equally distributed over the entire cross-section of the producer. The lower part of the producer casing is built up of removable cast-iron segments, and the base rotates on roller wheels instead of balls. Both this producer and the Kerpely are being largely used on the Continent, and are said to give very satisfactory results.

The composition of the gas from different producers of the ordinary type will vary very little when the same fuel is used, and, provided they are worked with care, the quality of the fuel, careful stoking, and regulation of air and steam supply will have far more influence on the quality of the gas than the particular form of producer.

Fuel for Producers.—All kinds of fuel are used in gas producers, from fine slack to fairly large coal; but probably the most economical form of fuel to use is good clean screened nuts about the size of walnuts, as, although costing more than common slack, it more than compensates for the extra cost by the regular working of the producer, better quality of gas, and less ash, &c., that has to be removed from the bottoms of the producers. The quality of the coal, whether a good gas coal or not, is also important; but although some coals give better results than others, owing to a larger percentage of volatile matter and freedom from ash, almost any coal *low in Sulphur*, if in fair mechanical condition, is suitable for producer work.

One of the great difficulties in producer work is the clinkering of the ash, and, so far as circumstances will permit, it is most desirable to select coals which produce as little clinker as possible.

Coke can be and is used to some extent with forced draught, but coal in some form is almost universally employed in steel works for gas production.

Charging Fuel in Producers.—The regular charging and even distribution of the fuel over the top surface area of the producer to maintain a bed of fuel of equal thickness in all parts is of great importance, and the various automatic mechanical feeds which have been devised all aim at this. A feeding device should as far as possible fulfil the following conditions:—

(1) It should be continuous, steadily supplying any required amount of coal during a given time, and the speed of the feed should be easily regulated, so that the coal supply can be adjusted to the amount of gas required in a given time.

(2) It should distribute the coal uniformly over the surface in the producer, making a body of equal thickness throughout, which offers an equal resistance to the air injected.

(3) It should also be simple in its construction, needing very little repairs, so that it may be run by unskilled labour.

A device known as the *Bildt Automatic Feed* is shown in fig. 110. It is very ingeniously designed on definite mathematical principles, and should, theoretically, give excellent results, and from the reports from America and elsewhere where it has been adopted these appear to be borne out in practice.

It consists, as will be seen from fig. 110, of a coal-holder resting upon and attached to the top of the producer, below which is placed a rotating distributing disc, A, provided with specially-constructed blades, *b* and *b'*, serving to distribute the coal evenly over the charging area. The disc is rotated by a vertical shaft resting upon the top of the coal-holder and a worm gearing, *d*, which in its turn is driven by cone-pulleys, *e*, by which the speed can easily and quickly be changed to feed more or less coal, as may be required.

The rotating of the disc will require only about $\frac{1}{10}$ H.P.

To suit different sizes of coal, the opening between the discharging mouth of the holder and the disc is adjusted by lifting the vertical shaft, which slides through the worm gear. This may be done by a screw-wheel at the upper end of the shaft.

The size of the coal is immaterial so far as the charging is concerned; lumps, dust, or both mixed, are equally well distributed.

The top of the rotating disc can be made level or sloping, but not

exceeding the angle of friction between the disc and the coal. The speed of the disc is for small gas producers about $\frac{1}{7}$ revolution per minute, and for big ones up to $\frac{1}{2}$ revolution in the same time. The disc is generally made of cast steel.

The holder, which can be made large enough to receive any desired quantity of coal, is filled through a hopper provided with a sliding damper. The coal is brought from any larger deposit and supplied by a coal-conveyor or by any other convenient method.

The apparatus can be applied to producers of any size, as it distributes the coal equally well over a large or small area.

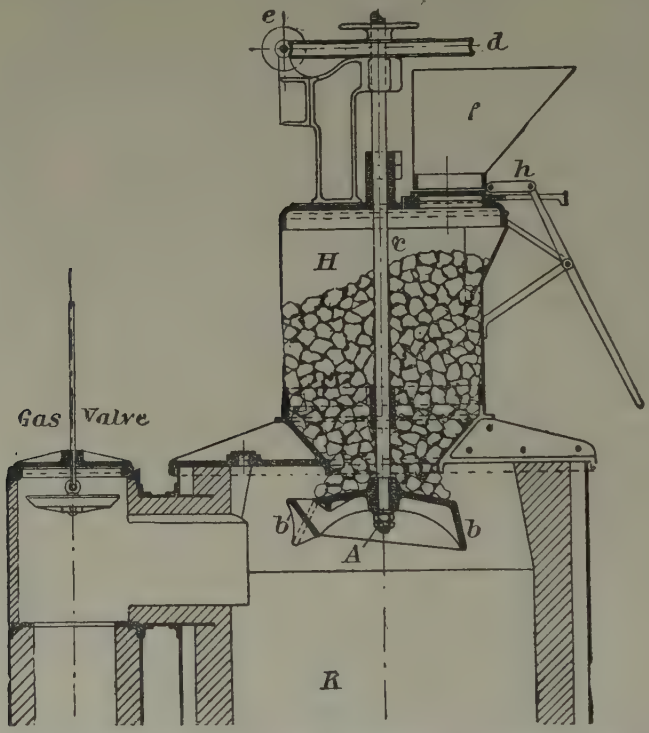


Fig. 110.—The Bildt Automatic Feed for Gas Producer—A, Distributing disc; H, coal-holder; K, producer; *c*, shaft for rotating A; *d*, *e*, gearing for rotating shaft; *b*, *b'*, blades on disc, A; *f*, hopper; *h*, lever for discharging hopper into holder, H.

Efficiency of Producers.—In large works, where batteries of 20 or 30 producers are frequently employed, it is a most important matter that these should give for the particular fuel used as large a yield of gas of good quality as possible, and the relation between the heating values of the coal charged into, and of the gas evolved from, the producer, constitutes a test of the efficiency of the producer. The efficiency of a producer may be defined as the ratio of the heat units capable of being obtained from the gas as it leaves the producer, and the heat units which the coal from which the gas is made is capable of yielding. Thus, if a certain quantity of coal has a heating value of 100, and the gas evolved from such a quantity of coal has a heating value of 50, the efficiency of such a producer would be $\frac{50}{100} = \frac{1}{2}$, or 50 per cent.

The heat given out by the gas may be divided into sensible heat and heat of combustion, and the efficiency of the producer will vary, according as the former is or is not included in the calculation. The cold-gas efficiency considers the gas to be at the temperature of the air, while in the calculation of hot-gas efficiency the sensible heat of the gas is taken into account. The direct method of finding the efficiency of the producer would be to measure the quantity of gas made from a given quantity of coal and burn samples of each in a calorimeter. This method is not usually feasible at works, and generally we have to calculate from the analysis of gas and coal how far the producer is working efficiently. Mr. Jenkins * proposes the following formula for calculating the efficiency of producers :—

$$\text{Cold-gas efficiency} = \frac{\mathbf{M} \times \mathbf{K} \times \mathbf{G}}{\mathbf{H}}.$$

M = { Heat of combustion of gas per kilogram of Carbon contained in it (calculated from analysis of gas with the aid of Table xxi. given below).

K = Proportion of Carbon in coal.

G = ,, of Carbon made into gas.

H = Heat of combustion of kilogram of coal (determined by experiment).

The calorific power (the heat of combustion per unit volume) of a gas divided by the weight of Carbon in a cubic metre gives the heat of combustion of the gas per kilogram of Carbon—*i.e.*, **M** (or figure of merit).

The calorific powers of gases given by different authorities vary considerably, but any of the following tables are sufficient for all practical purposes, and Mr. Jenkins, in his paper, uses that of Messrs. Winkler and Lunge :—

TABLE XX.—Calorific Power of Different Gases.

	Calories per Cubic Metre.		
	Faure and Silbermann.	Julius Thomsen.	Winkler and Lunge.
CO, ...	3,014	3,044	3,066
H, ...	2,389	2,631	2,581
CH_4, . . .	8,498	8,417	8,697
C_2H_4, . . .	14,009	13,848	14,045

The following table gives the amount of Carbon in one cubic metre of different gases :—

TABLE XXI.

Gas.	Kilogrammes of Carbon per Cubic Metre.
Carbon Dioxide (CO_2), . . .	0·5376
Carbon Monoxide (CO), . . .	0·5376
Marsh Gas (CH_4), ...	0·5376
Olefiant Gas (C_2H_4), ...	1·0752
Hydrogen and Nitrogen, . . .	0·0000

In the above equation **M** is sufficient to measure the quality of the gas, if only one kind of coal is used. **K** depends on the quality of coal,

* Efficiency of Gas Producers, *Min. of Proceedings of Inst. Civil Engineers*, vol. cxxiii., p. 328.

its percentage of ash, &c. G measures the grate efficiency—in other words, the percentage of Carbon passing away unburnt with the ashes.

The cold-gas efficiency considers the gas as leaving the producer at the temperature of the air, and the *hot*-gas efficiency may be obtained from it by means of the following formula:—

$$\text{Hot-gas efficiency} = \text{cold-gas efficiency} \times \left\{ 1 + \frac{\text{Sensible heat per cubic metre of the gas}}{\text{Calorific power of the gas}} \cdot \right\}$$

The sensible heat per cubic metre = (temperature of gas − temperature of the atmosphere) × "volumetric specific heat of the gas."

By the volumetric specific heat is meant the heat required to raise the quantity of gas 1° C. which, at standard temperature and pressure, would occupy 1 cubic metre.

The following tables * give specific heats of the different gases, all of which, except CO_2 (whose specific heat at different temperatures is given separately), are constant for different temperatures:—

TABLE XXII.—Volumetric Specific Heat of Different Gases.

Gas.	Calories per Cubic Metre per Degree C.
Oxygen (O_2),	0·313
Hydrogen (H_2),	0·305
Nitrogen (N_2),	0·306
Carbon Monoxide (CO),	0·306
Marsh Gas (CH_4),	0·425
Olefiant Gas (C_2H_4),	0·506

TABLE XXIII.—Volumetric Specific Heat of Carbonic Acid at Different Temperatures.

Temperature (t).	Mean Calories per Cubic Metre of Gas per Degree between 0° C. and t° C.
t = 400	$Cp_e - t$ = 0·467
t = 500	,, = 0·487
t = 600	,, = 0·507
t = 700	,, = 0·525
t = 800	,, = 0·544
t = 900	,, = 0·562
t = 1,000	,, = 0·580
t = 1,100	,, = 0·598
t = 1,200	,, = 0·615

$Cp_e - t$ indicates the mean value of specific heats at constant pressure between 0° C. and t° C.

In the above formula no account is taken of sensible heat carried over by any steam in the gases, and if necessary a correction must be made for this, the percentage of steam being first determined by experiment by aspirating a given quantity of gas through a drying tube. The correction is, however, of very small importance, unless the amount of steam is

* Calculated by Mr. Jenkins from figures given by Professor Akerman, *Beitrag zur Entwicklung der Frage der Heizgasgewinnung.*

abnormal, and is rarely worth making, involving as it does a special test of the gas, and a very troublesome and lengthy calculation.

The following is a numerical example of the calculation of the efficiency of a producer from the Jenkins formula :—

Example of Calculation of Efficiency.

A Rectangular Brick Producer giving poor gas.

$$\text{Cold-gas efficiency} = \frac{M \times K \times G}{H}.$$

Proportion of Carbon in coal, . . 0·750 . . . . = K.
,, ,, made into gas, . 0·964 . . . . = G.
Heat of combustion of coal, . . . 8·000 calories per kilogram = H.

M is found as follows :—

Volumetric Analysis of Gas.	Calorific Power.	Carbon in Gases.
Per cent.		Per cent.
CO_2, 7·5	...	7·5 × ·5376
CO, 18·5	18·5 × 3·066 566	18·5 × ·5376
CH_4, 0·7	0·7 × 8·607 60	0·7 × ·5376
H, 10·4	10·4 × 2·581 268	...
N_2, 62·9	...	...
100·0	894	$\frac{26·7 \times ·5376}{100}$ = 0·144 kg. Carbon

$$\therefore \text{ Figure of merit} = \frac{894}{0·144} = 6{,}210 \text{ or } M.$$

$$\text{Cold-gas efficiency} = \frac{\overset{M}{6{,}210} \times \overset{K}{0·75} \times \overset{G}{0·964}}{\underset{H}{8·000}} = 0·562.$$

Temperature of gas = 1° C.

Hot-gas efficiency is found as follows :—

	Vol. sp. heats.	
CO_2,	7·5 × 0·580	= 4·35
CO,	18·5 × 0·306	= 5·66
CH_4,	0·7 × 0·425	= 0·30
H,	10·4 × 0·305	= 3·16
N_2,	62·9 × 0·306	= 19·25

} = 0·3272 (mean specific heat).

Sensible heat per cubic metre of gas = 1000° × 0·3272 = 327·2.

$$\text{Hot-gas efficiency} = 0·562\left(1 + \frac{327}{894}\right) = 0·756.$$

Nothing is probably of greater importance in fuel economy than keeping a regular and systematic check upon the working of the producer by frequent analyses of the coal used, the ashes, and the evolved gas, as it is not an uncommon thing to find producers working under similar conditions as regards fuel varying in efficiency from 50 to 66 or 75 per cent., which means that one producer is burning 70 tons of fuel to produce the same amount of heat as the other is producing from only 50 tons. In some American works, samples of the gas are taken from the producer once or twice every twelve hours, an average sample from the main gas culvert every two hours, and the whole results tabulated and plotted each week. The cost of this is only equal to a few tons of fuel per week, and if this example, combined with frequent analyses of ashes, &c., were followed in

all our English works, the saving in fuel would probably astonish some of our steel makers.

Under normal conditions of work when an average amount of steam is used, as in the Siemens, Wilson, or Dawson type of producers, carbonic acid should average about 5 per cent. and should never exceed 7 per cent. A higher percentage than this, especially if the gas has a high temperature on leaving the producer, may be taken as a sure indication of bad working

The following are fairly typical analyses of gas from producers when working well :—

TABLE XXIV.

	Wilson.	Dawson.	Siemens.	Talbot.*	American Producer Gas.	Forced Blast without Steam.
Carbon Dioxide, .	5·10	5·50	4·80	2·91	5·20	3·80
Carbon Monoxide, .	23·42	22·90	24 80	33·35	22·8	27·00
Hydrogen, . .	12·00	11·55	8·70	13·86	8·5	7·60
Marsh Gas, . .	2·90	3·10	2·30	...	2·4	3·60
Olefiant Gas, . .	0·40	0·30	...	...	0·4	0·35
Nitrogen, . . .	56·18	56·65	59·6	49·90	60·3	57·65

The calorific power of a gas is of great importance, as although the percentage of Carbon Monoxide, Hydrogen, &c., for producers working under similar conditions, may indicate the heating value of the gases, if taken alone, and compared with the gas from producers working under different conditions, with varying percentages of steam, erroneous conclusions may be drawn.

In the following Table xxv. are summarised the results obtained by Prof. Bone and Dr. R. V. Wheeler † during an important investigation on the use of steam in gas producer practice. For these experiments a producer of the Mond type was used, and trials extending over a full week were made under each set of conditions examined. The first series of trials was made with a depth of incandescent fuel of 7 feet, and in the second series this depth was reduced to 3 feet 6 inches : this thickness of fuel not only permits of very high rates of gasification, and keeps clinkering difficulties within easily manageable proportions, but is also sufficient to accomplish the decomposition of nearly all the steam introduced in the blast (*i.e.*, with a saturation temperature not exceeding 60° C.), and to reduce the amount of Carbon Dioxide in the gas to 5 per cent. or even less. The influence of successive increments of steam, with consequent lowering of the temperature of the incandescent fuel is that the reaction $C + 2H_2O = CO_2 + 2H_2$, comes more and more into play at the expense of the reaction $C + H_2O = CO + H_2$, and the equilibrium points of the reversible reactions $CO + H_2O \rightleftharpoons CO_2 + H_2$ and $2CO \rightleftharpoons C + CO_2$ shift more and more to the right hand. Thus, successive increments of steam in the blast increase the percentage of Carbon Dioxide and Hydrogen, but reduce the percentage of Carbon Monoxide in the resulting gas.

* This is the average of five analyses kindly supplied me by Mr. Mannaberg, of Frodingham, where a Talbot producer is working. The hydrocarbons were not determined separately, but are included in the CO and H, which makes these higher than they would otherwise be.

† *Iron and Steel Inst. Journ.*, 1907, vol. i., p. 126 ; 1908, vol. iii., p. 206.

TABLE XXV.—Effect of Introduction of Different Quantities of Steam on the Composition of Producer Gas.

Average depth of incandescent fuel,	3 feet 6 inches.					7 feet.				
Average rate of gasification (day shift) per hour per producer,	22·5 cwts.					11·5 cwts.				
Steam saturation temperature,	45°	50°	55°	60°	70°	60°	65°	70°	75°	80°
Percentage Composition of gas. Carbon Dioxide,	2·35	2·50	4·40	5·10	9·25	5·25	6·95	9·15	11·65	13·25
Carbon Monoxide,	31·60	30·60	28·10	27·30	20·85	27·30	25·40	21·70	18·35	16·05
Hydrogen,	11·60	12·35	15·45	15·50	19·75	16·60	18·30	19·65	21·80	22·65
Methane,	3·05	3·00	3·00	3·05	3·45	3·35	3·40	3·40	3·35	3·50
Nitrogen,	51·40	51·55	49·05	49 05	46·70	47·50	45·90	46·10	44·85	44·55
Total combustibles,	46·20	45·95	46·6	45·85	44·05	47·25	47·10	44·75	43·50	42·20
Yield of gas, cubic feet at 0° C. and 760 mm. per ton of coal,	133,700	132,500	132,700	135,000	...	138,250	134,400	141,450	145,800	147,500
Steam added to blast, lbs. per lb. of coal,	0·2	0·21	0·32	0·45	...	0·45	0·55	0·80	1·10	1·55
Percentage steam decomposed,	All	All	All	76·0	...	87·0	80·0	61·0	52·0	40·0

Under ordinary conditions of producer work it is important that the amount of steam in the gas, as it leaves the producer, should not be high, as it carries with it a comparatively large amount of sensible heat, which is lost if the gas is used cold, and partially lost if the gas is used hot.

The low efficiency of a producer may result from various causes, amongst the most common being the burning of gas in the producer itself, due probably to careless stoking, so that air channels are formed in the bed of fuel; or, possibly, defective construction of the producer may cause the same result. The gas produced under these conditions will be high in Carbon Dioxide, and low in Carbon Monoxide and Hydrogen, and will, of course, have a very low calorific power. The following is an analysis representing a very bad case* :—

Carbon Dioxide (CO_2),	10·20	per cent.
Carbon Monoxide (CO),	11·80	,,
Marsh Gas (CH_4),	2·40	,,
Hydrogen (H),	8·80	,,
Calorific Power,	790	

One of the surest indications of burning of the gas in the producer is a high and rapidly varying temperature of the gas; and there is probably no better way of controlling the working of the producer in this respect than to have an automatic record of the temperature of the gas as it leaves the producer. This, now that pyrometers of the Le Chatelier type are being used in all our leading works, could be arranged in many cases without any difficulty. A pyrometer in the gas culvert, as near as possible to the producer, and

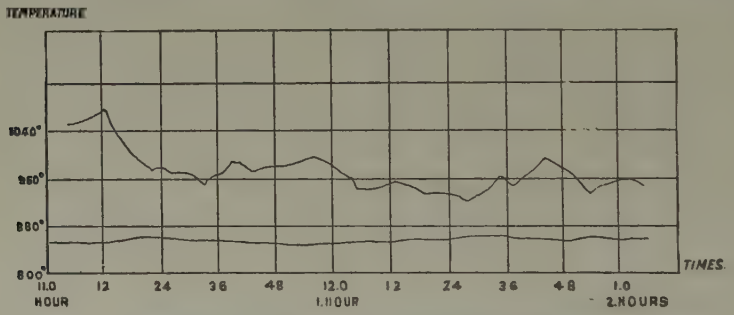


Fig. 111.—Temperature Variations in Producer Gas—Upper curve when working badly; lower curve when working well.

connected with a recorder, would give perhaps a better regular indication of the continuous working of the producer over a period of time, than even frequent analyses, and would be an excellent check on irregular stoking. It is, however, advisable to have analyses as well, as by considering the temperature and the analysis of the gas together not only are we able to form a definite opinion as to the working of the producer, but apart from this, the actual colorific value of the gas can be calculated from the analysis. Under ordinary conditions the temperature of the gas leaving the producer should not exceed 750° to 850° C., and the variations should be slight. From information received by the author, he is of the opinion that the best results are obtained when the gas is about 750°, although it will vary somewhat with the fuel used. The diagram (fig. 111), by Mr. Jenkins, shows the variation in temperature of the gas from a producer when working badly and when working well.

* Jenkins, *loc. cit.*, p. 341.

Taking Samples.—The advantage of obtaining fair average samples of the coal, gas, and ashes need not be dwelt upon, but in each case, to get reliable results, they should be the mean of 6 or 7 samples taken over a period, say, of one week. In taking the gas samples, Stead's* gas sampler is extremely handy, samples should be collected every two or three hours, and the average of 6 or 8 samples taken to represent the gas for the particular 24 hours.

Water Gas.—As stated previously, when steam is passed through a bed of red-hot Carbon it is decomposed, with formation of Carbon Monoxide and Hydrogen, reactions which are endothermic, or attended with absorption of heat, so that unless heat is supplied from an outside source the incandescent Carbon is rapidly cooled, and the reactions cease. Provided no air is injected with the steam a gaseous mixture, consisting almost entirely of Carbon Monoxide and Hydrogen, is obtained, and this is known as water gas, which is most useful for certain metallurgical operations, where great local intensity of heat is required. In preparing this gas on a large scale, it is usual to raise the fuel to a state of incandescence by the injection of air, which produces ordinary producer gas, and then to shut off the air and inject steam through the incandescent Carbon, generally in the reverse direction. It is customary to blow up with air for about eight to ten minutes, and then to inject steam for about four minutes, and by this means we get an alternate production of producer and water gas. As for most operations it is necessary to have a continuous supply of gas, whether it be producer or water gas, it is generally essential to have two gasholders, one for storing each gas, so that they can be used as required. Water gas has been tried at several works, for open hearth steel furnaces, but, with the exception of one or two small furnaces for making steel castings, has not been a success, and attempts to use a mixture of the water and producer gas, although tried at various works, have not been so successful as to lead to its general adoption.

For special work, such as tube welding, etc., water gas is most useful, but for open hearth practice it is not suitable, as the great intensity developed by its combustion is not essential to the process, and leads to great expense for repairs due to unnecessary wear and tear on the furnace. It is, therefore, more economical to use good producer gas, which gives all the heat required, and can be supplied continuously from the producer, without any storing in holders, or mixing with other gas. It should be borne in mind that the great intensity of the flame produced by combustion of water gas is not due to the specially high calorific intensity of Hydrogen present, but to the fact that it is not diluted by an inert gas like Nitrogen, and consists entirely of combustible gases. Even in works where there is a demand for both producer and water gas, the former made by blowing up the producer is generally so saturated with water vapour that its thermal value is very low, making it useless for many purposes, where high temperatures are required, unless all the water vapour is first condensed. Apart from the intermittent supply the comparatively small amount of water gas, compared to the amount of producer gas made in a given time, has been a most serious drawback to its general adoption in metallurgical works, and although many attempts have been made to produce water gas continuously, they have only comparatively recently been attended with success.

It will be remembered that when Carbon is burnt to Carbon Dioxide, more than three times as much heat is produced as when it is burnt to Carbon

* *Iron and Steel Inst. Journ.*, 1884. vol. i., p. 187.

Monoxide, and if the fuel in the producer could be burnt so that the gas left the producer as Carbon Dioxide instead of Carbon Monoxide, three times as much heat would be accumulated in the fuel, and be available for the decomposition of steam, and consequently the quantity of water gas would be correspondingly increased. This is what has been effected in the process known as the Dellwik, or Dellwik-Fleischer. We have seen that under *ordinary circumstances* in a producer Carbon is burnt to Carbon Monoxide (**CO**); how then is it possible to burn Carbon to Carbon Dioxide (CO_2), and prevent its reduction to Carbon Monoxide during its passage through a thick bed of fuel? Messrs. Dellwik and Fleischer have shown that this can be effected by working at a higher pressure of blast, so that in a given space of time each unit of Carbon is brought into contact with more Oxygen than usual. In this way the conditions of chemical equilibrium for the particular temperature are changed, and the point where Carbon combines with only one atom of Oxygen is moved upwards, so that even at 1,000° or 1,200° C. Carbon Dioxide (CO_2) is formed, and is not reduced again to Carbon Monoxide (**CO**), because the excess of Oxygen enveloping it presents other conditions than those present in former cases considered. With this process it is only necessary, therefore, to blow up the producer with air for $1\frac{3}{4}$ minutes, as against 10 minutes with ordinary water gas process, and steam can be injected for 8 to 10 minutes for gas making.

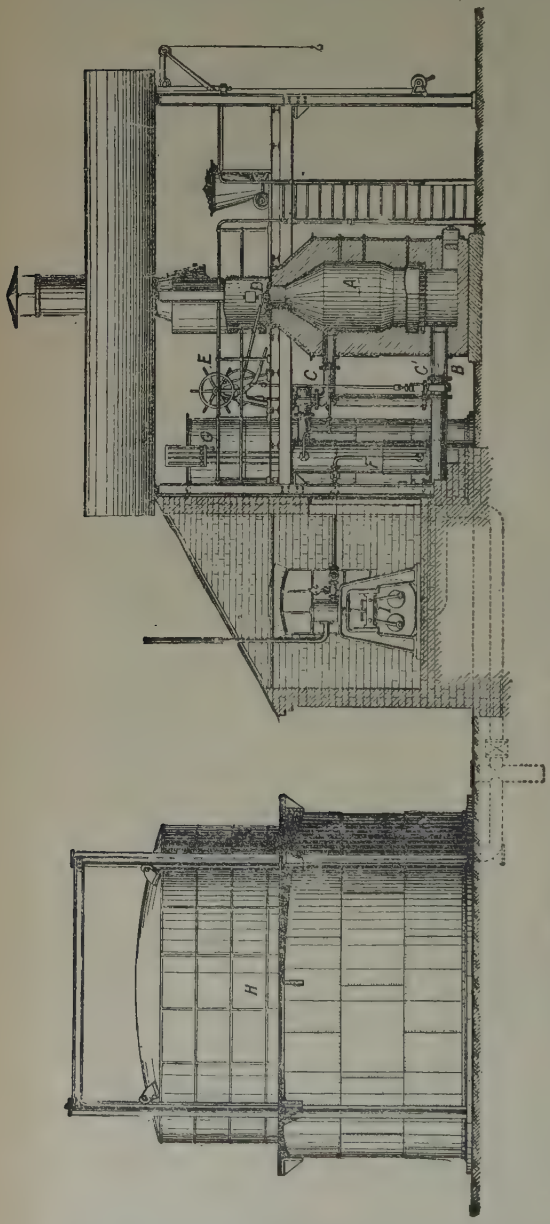


Fig. 112.—The Dellwik-Fleischer Water-Gas Plant. A, generator; B, blast inlet; CC′, gas outlets (the lower, C′, behind the blast pipe); D, stack and charging valve; E, interlocking valve gearing; F, steam superheater; G, scrubber; H, gasholder; I, blower and engine.

as against 5 minutes. The time of blowing and injecting steam will vary with the class of fuel used, and the author has private information respecting two plants in England, in one of which they blow up for 80 seconds and inject steam for 10 minutes; in the other the blowing lasts 1 minute, and steam injection 8 minutes. The gas from blowing up does not contain appreciable quantities of **CO**, but from 17 to 18 per cent. of Carbon Dioxide (CO_2), and 1 to 2 per cent. of oxygen, and is, of course, allowed to escape out of the stack. The water gas has the following composition :—

CO,	39·65
H,	50·80
CH_4,	0·82
$C_n H_{2n}$,	0·05
CO_2,	4·65
O,	0·20
N,	3·83
	100·00

As the result of numerous experiments it has been found that 30 to 33 lbs. of coke produce 1,000 cubic feet of water gas, as against 45 to 50 lbs. required by the best of the old processes, and give a utilisation of 65 to 70 per cent. of the fuel, as against 45 per cent., only 30 per cent. being lost by radiation, and carried away by the gases escaping to the stack.

Fig. 112 illustrates the latest form of the Dellwik-Fleischer producer, in which A is the generator, fitted with fire-bars near the bottom, and lined with fire-brick, B is the blast-pipe which admits the air-blast below the fire-grate, C and C′ are gas outlets, the upper one, C, being in use when the steam is admitted at the bottom, and the lower one, C′, not seen in the sketch, being in use when the steam is admitted at the top; D is the stack for the outlet of waste gases during the heating up with air, this also shows the charging arrangement; E represents the interlocking valve gearing used for reversing the direction of the steam and the water-gas at intervals; F is the steam superheater, from which two conducting pipes enter the generator, one near C and the other near C′; G is the scrubber, through which the water-gas passes on its way to the gasholder H; I is the blower and engine. In use, the steam is alternately blown in at the top and bottom, the water-gas being drawn off at the bottom or top as the case may be.

Natural Gas.—In certain localities in America and elsewhere, in boring for oil, vast reservoirs of gas, under great pressure have been tapped. This gas is now carried immense distances in pipe lines, and distributed to the various works for steel making and other purposes. The pressure at which

	Pittsburg. Natural Gas.	Pennsylvania. *	
Hydrogen,	22·00	22·50	6·10
Marsh Gas,	67·00	60·27	75·44
$C_n H_{2n}$ gases (olefiant gas),	6·00	6·80	18·12
Carbon Monoxide,	0·60	Trace.	Trace.
Nitrogen,	3·00	...	...
Carbon Dioxide,	0·60	2·28	0·34

* Sir Boverton Redwood, *Petroleum and its Products*, vol. i., p. 223.

the gas escapes varies from 100 to 200 lbs. on the square inch, and enables it to be taken great distances. It gives excellent results in steel making, being practically free from non-combustible gases, and of such high calorific power, that no regeneration of the gas is necessary, the air only being superheated. The foregoing table gives typical analyses.

Unfortunately we have not so far discovered any large stores of natural gas in this country, and we have to rely entirely upon gas made from coal or coke for steel manufacture, and in this respect are seriously handicapped in competing with American manufacturers.

CHAPTER VII.

THE OPEN HEARTH OR SIEMENS PROCESS.

The process of manufacturing steel in the open hearth regenerative furnace, which we owe chiefly to the genius of Sir William Siemens, is the only process which has in any way proved a serious rival to that of Bessemer. The difficulty of obtaining a sufficiently high temperature to maintain a large quantity of decarburised iron in a fluid condition was the chief obstacle to the solution of the problem, and it was only after many experiments, involving great expense and labour, that the efforts of Sir Wm. Siemens and his brother were crowned with success. They first gasified the fuel in a separate furnace called a producer, and then raised this and the air necessary for its combustion to a high temperature by means of the waste heat derived from the previous combustion stored up in fire-brick checkered chambers, which they called regenerators. They then conducted the superheated gas and air by separate flues to the hearth of the furnace, where combustion took place with the production of an extremely high temperature. Great difficulties were experienced in the early days in obtaining for the roofs of the furnaces refractory materials which would both withstand the high temperature and the contraction and expansion; but these were gradually overcome, and in 1867 to 1868 the success of the process was demonstrated at an experimental works at Birmingham, large quantities of steel being made from old rails and similar material. Gradually the problem of desiliconising and decarburising pig-iron, with and without steel scrap, by means of iron ore as the oxidising agent, was worked out, and in 1868 the Landor Steel Company was started. In France, Messrs. P. & E. Martin also attacked the problem; but, instead of using ore, they worked with steel scrap and pig-iron alone, dissolving the scrap in a bath of molten pig until, by the diluting down of the impurities combined with their partial removal by oxidation, they produced a steel of the required grade. This process was known as the Siemens-Martin, as distinguished from the Siemens process, in which ore and pig alone were used; but the distinction has long ceased to be of any importance, the almost universal practice now being to use both ore and scrap with the pig, especially in this country.

The original furnaces built at Landore were only of 3 to 4 tons capacity, but now it is by no means uncommon to find furnaces working charges from 40 to 50 tons, and some metallurgists anticipate that the 100-ton furnace will be the one of the future. Furnaces of a larger capacity than this are now in operation working the Talbot process, which is a modification of the Siemens process.

General Description of Furnace.—The Siemens furnace consists of a large hearth built of refractory material, upon which the metal is melted without contact with any solid fuel. At each end are arranged two chambers filled with checker fire-bricks, through which the air and gas pass on their way into the furnace, and through which the products of combustion pass at the other end on their way to the stack. One of these regenerators on each side is called the gas, and the other the air regenerator, and they are separated by substantial walls to prevent the air and gas mixing in any way before it reaches the hearth of the furnace. The furnace and regenerators having been heated up, gas and air are admitted through their respective regenerators on one side of the furnace, and these, by circulating amongst the hot brickwork, become heated, and finally meet in the hearth of the furnace where combustion takes place. The products of combustion then pass indiscriminately through the gas and air regenerators at the other side, and give up the greater part of their heat to the brickwork through which they circulate on their passage to the stack. At regular intervals, depending somewhat upon the way the furnace is working, the direction of the gas and air is reversed by means of valves, so that the regenerators are alternately heated up by the products of combustion and cooled by the incoming air and gas. There are altogether four valves apart from the chimney damper; two are ordinary mushroom valves, one of which controls the admission of the air and one the gas, and two are known as reversing valves for altering the direction of the current of air and gas respectively.

The diagrams in Plate vii. illustrate the general arrangements of the furnace, showing how both gas and air are admitted to the furnace, and the arrangement of valves for controlling and reversing the direction of both.

The Siemens process, like the Bessemer, can be worked either with an acid or a basic lining, Hematite or Phosphoric pig being used according to the lining adopted. The removal of the impurities in either case depends broadly upon the same principles as in the Bessemer—viz., the oxidation, the retention, and removal of such impurities in the slag. In the basic Siemens lime additions are made to form a stable Phosphate exactly as in the basic Bessemer.

Before describing either process in detail, the plant employed, which is common to both, will be described, as the gas producers, regenerators, furnace, valves, &c., are the same for both acid and basic, except in some minor details.

The Furnace.—Variations in the construction of furnaces to meet special requirements are very numerous, but after many experiments with round and elliptical furnaces, experience has demonstrated that a rectangular furnace, as originally used by Sir William Siemens, gives by far the best results in actual practice. The body of the furnace should be built of iron or mild steel plates, lined internally with the best silica bricks, and should be carried on steel girders quite independent of the regenerator arches, so that air can freely circulate underneath the bottom of the furnace, as shown in Plate viii. If an open space is thus left under the furnace bottom, and regenerators are kept well to each end, in the event of the metal breaking through the bottom there is no danger of its getting into the regenerators. In the old type of Siemens furnace it was usual to build the hearth (as shown in fig. 113) over the regenerators, and to use the regenerator arches to support the furnace, but this is never done now. The whole structure must be most strongly braced together by tie-rods to control the expansion of the refactory materials, and probably the best plan is to encase the entire body of the furnace in steel plates, well rivetted together and strengthened by strong supports secured by tie-rods across the top of the furnace. The

bottom of the furnace is usually made of cast-iron plates, but these may be of steel. The walls, roof, and the whole of the interior except the actual hearth on which the molten metal has to rest, are built up with best silica

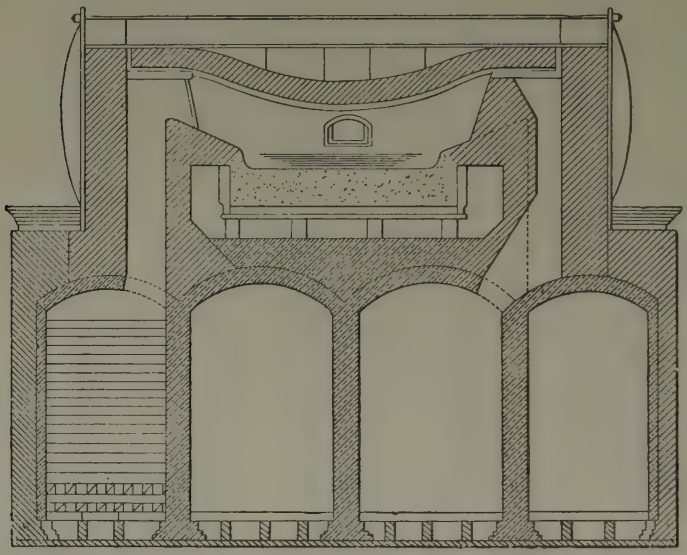


Fig. 113.—Old-fashioned type of Siemens Furnace, with dip roof and body of the furnace supported on the regenerator arches.

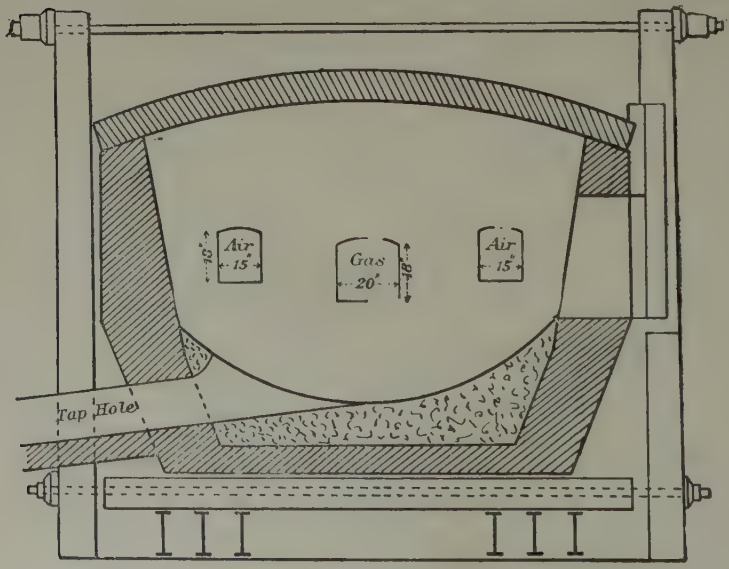


Fig. 114.

fire-bricks (as shown in the accompanying sketch), the hearth itself being lined either with silica sand or with basic material, according to conditions of

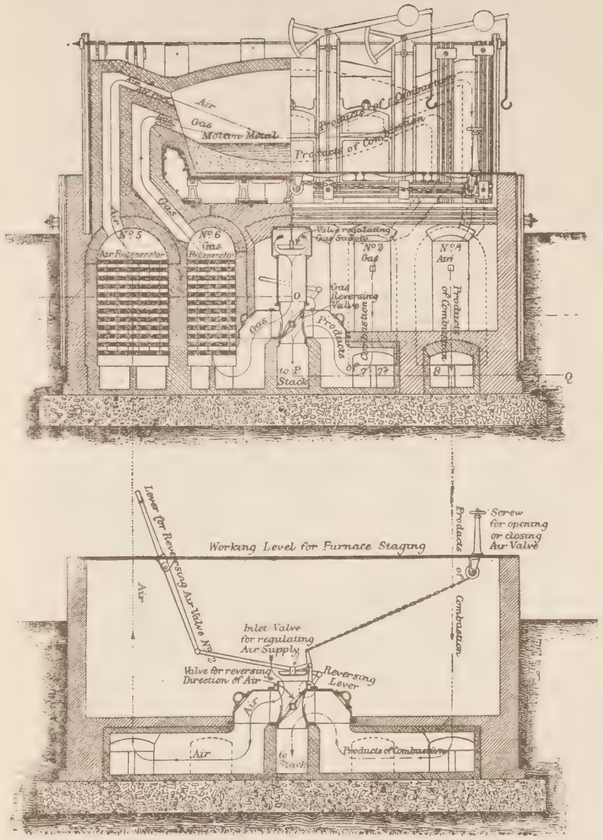
Valves.—Valves marked gas inlet and air inlet are for regulating the quantity of gas and air admitted. Valves marked gas and air reversing valves are for reversing the direction of the gas and air in the furnace, and are quite independent of the inlet valves. The general valve arrangement for controlling the supply and reversing the direction of the current is shown in separate sketches (figs. 119 and 120). There are four valves in all—one gas and one air inlet, and one gas and one air reversing. By raising or lowering the gas or air inlet by means of the screws G and A, more or less gas and air is admitted. By swinging the reversing valves over into the position shown in these figures, the direction of the gas and air is reversed, and instead of passing through the left-hand regenerators on their way to the furnace, as shown by arrows in figs. 115 and 116, they pass through the right-hand regenerators.

Fig. 115 is a longitudinal view of the furnace, partly in section and partly in elevation. The gas inlet and gas reversing valves are shown, but the air valves being behind the gas valves cannot be seen in their actual position, so are shown in a separate sketch projected below (fig. 116), the arrows indicating the direction taken by the air and products of combustion. The actual position of these gas and air valves in relation to each other will be seen by referring to the transverse section (fig. 117), and the sectional plans (fig. 118).

In the diagram gas and air are shown entering the furnace through the ports or inlets from the regenerators on the left-hand side of the sketch, and the products of combustion passing through the regenerators on the right-hand side on their way to the stack, as indicated by the arrows. When the reversing gas and air valves are swung over into this position, shown in figs. 119 and 120, the gas and air enter on the right-hand side and the products of combustion leave by the left. The inlet valves are not altered when reversing.

Fig. 117 shows a transverse section through the tapping hole of the body of the furnace, with ladle in position, ready for casting, and is intended, aided by more detailed drawings given elsewhere, to give a general idea of the construction of the furnace.

Pig-iron and scrap steel are charged in the cold state on to the hearth of the furnace, and when it is melted iron ore is added to oxidise the impurities. When the conversion into steel is complete an iron bar is driven through the taphole, shown in fig. 117, by means of sledges, to remove the stopping of fireclay which has been rammed in previous to starting the furnace, and the metal flows down the spout into a ladle standing in the position shown. When the metal has all passed into the ladle, the support to the metal spout near the furnace is knocked away, the spout swings over on the hinge shown, and the slag flows into the slag hole.



Figs. 115 and 116.

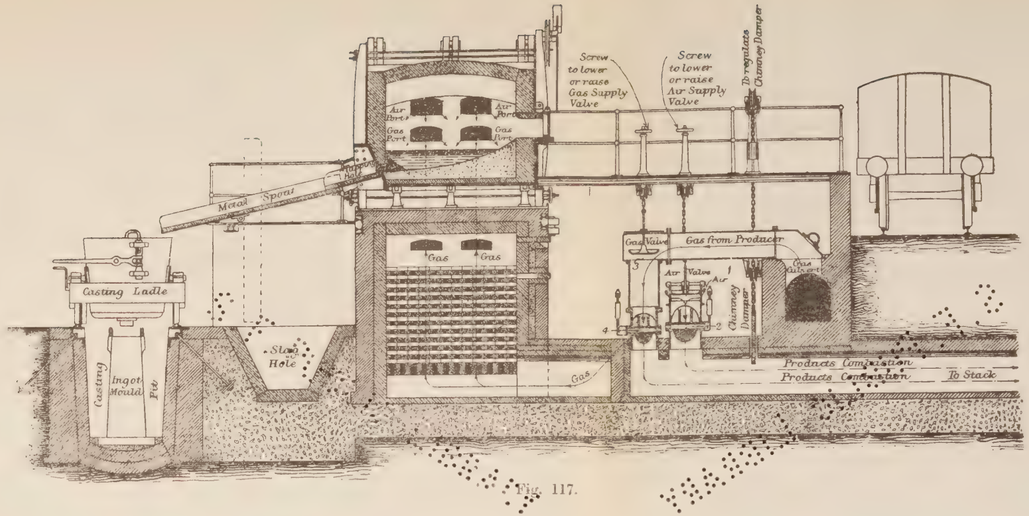
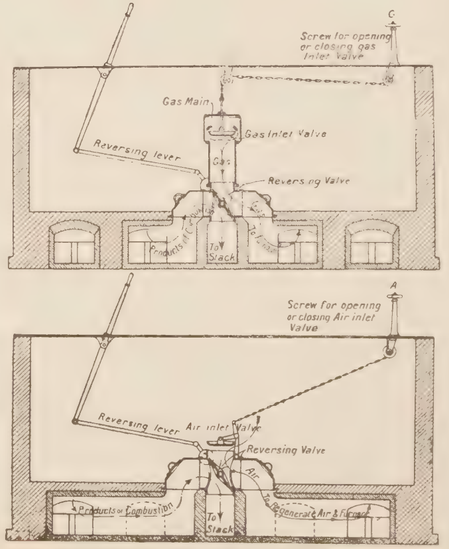


Fig. 117.



Figs. 119 and 120.

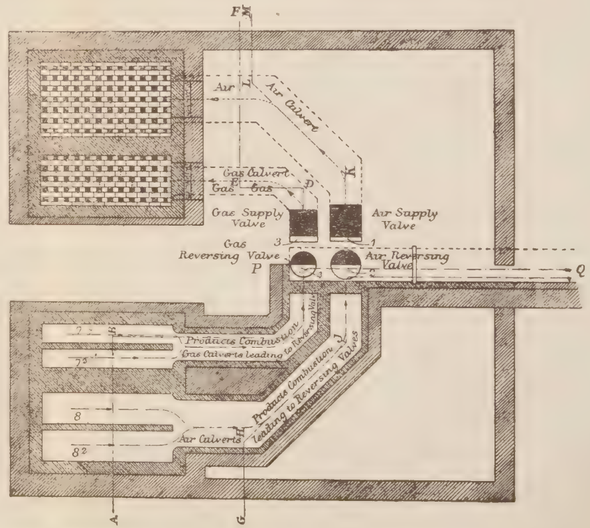


Fig. 118.

working. On Plate viii., figs. 123-126, are given the sectional elevations and plan of a modern Siemens furnace, designed by the late Mr. Bernard Dawson for basic work, but equally applicable for acid steel manufacture. The body of the furnace is rectangular, supported on girders independent of the regenerator arches, and the air regenerators are $\frac{1}{4}$ to $\frac{1}{3}$ larger than the gas. The gas enters the hearth of the furnace from the regenerators through two openings known as "ports," and the air through three, and these are arranged side by side. The section on J, K shows these "ports;" the solid brickwork through which they pass is known as the "block," and must be very strongly built to prevent the "ports" giving way, owing to the intense heat and contraction and expansion to which they are subjected.

It is of the greatest importance in furnace work that the combustion of the gas in the furnace hearth should be as perfect as possible, for not only will the calorific efficiency of the furnace as a heating machine depend upon this, but also the calorific intensity of the flame, so important for rapid production of good steel. That the combustion is largely affected by the way the gas and air enter the furnace—that is to say, by the position of the "ports" and by the form of the roof—there can be little doubt; but as to what is the best arrangement, considerable difference of opinion exists.

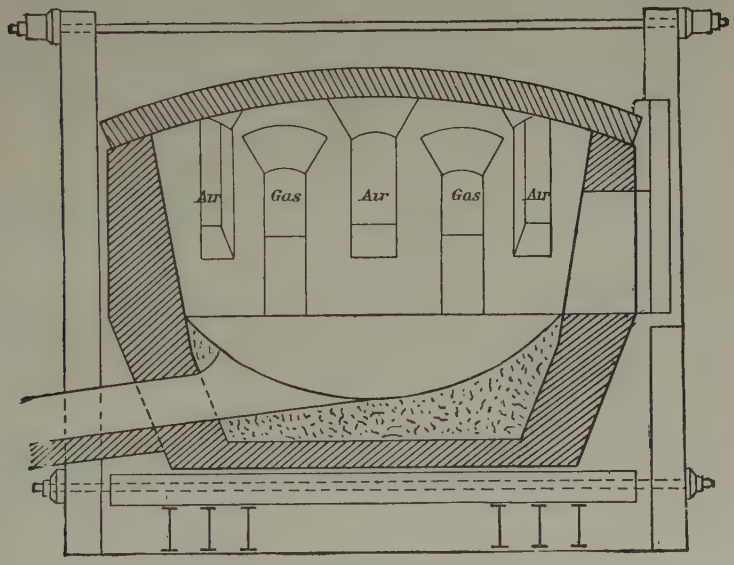


Fig. 121.

We find furnaces doing very good work with one large gas port, and with an air port on either side (as shown in fig. 114); others with two gas and three air ports, as shown in fig. 121 and in the diagrams of the Dawson-Siemens furnace (Plate viii., figs. 123-126); and others with two gas ports, the usual height above the fore plate, and two air ports near the roof (fig. 122); or, again, others with two gas ports and two air ports above them, as shown in Plate vii., fig. 117. The position of the ports will to some extent depend upon the roof. In Sweden very high-roofed furnaces, with dome-shaped arches, and so-called "gallery ports"—*i.e.*, gas and air ports side by side at same level—are said by Mr. Odelstjerna * to give very good results

**Trans. American Inst. Mining Engineers*, 1894.

and to induce very perfect combustion. Taking all things into consideration, the arrangement of ports, shown in fig. 122, is as good as any, and it admits of the blocks being made very solid and strong, a very important matter from a practical point of view. In the original form of Siemens furnace, the roof was made with a dip to the centre (as shown in fig. 113) with the object of deflecting the flame on to the bath of metal, but the roof was found to be rapidly burnt away; and in all modern furnaces the best results are obtained with fairly high roofs, the inclination of the gas and air ports being quite sufficient to cause the flame to impinge on the bath. With a large arch thrown over the entire hearth, springing from wails about 3 feet 6 inches to 5 feet above the fore-plate level, according to the size of furnace, and with a rise of about 15 inches in the centre, a large combustion chamber is provided, in which perfect combustion can take place with the least possible destructive action on the roof.

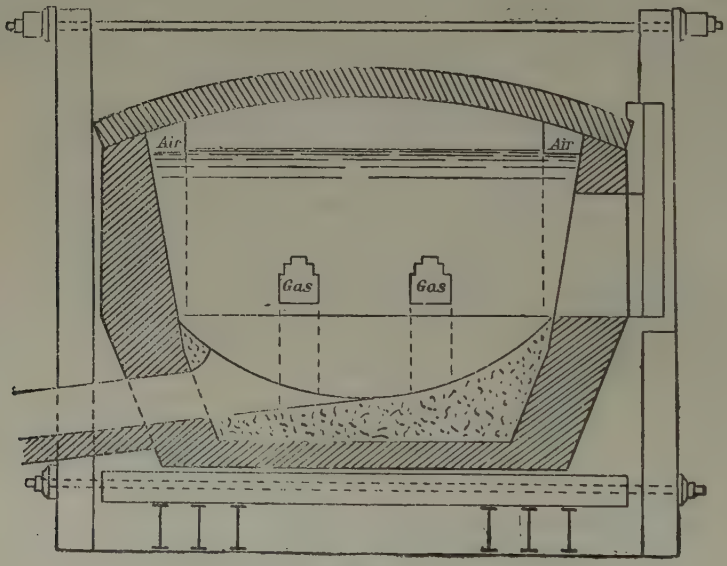
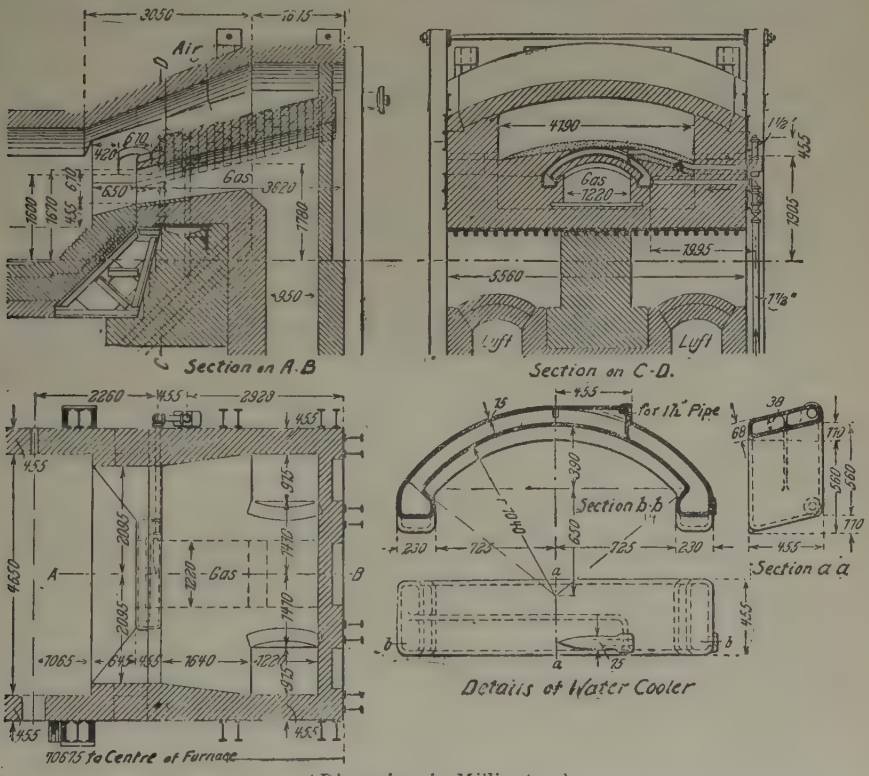


Fig. 122.

The increase in the dimensions of modern furnaces, together with the more general use of molten metal in Basic practice, has put a very severe strain on the refractory linings of the furnaces, and considerable attention has been given to modifications in construction with a view to increasing the life of the furnace. The "blocks" in which the ports are built are especially subjected to the cutting action of the flame, and the fluxing and abrading action of solid particles of ore, lime, etc., carried by the gases, and require frequent repairs compared with the body of the furnace, and various devices have been tried to facilitate such repairs and to reduce the wear and tear as much as possible. In some cases air-cooled hollow castings are introduced into the "block," which help to prolong the life of this part of the furnace under the extremely high temperature to which it is exposed, combined with contraction and expansion due to cooling down more or less after every charge (see Plate ix.). Owing to the great difficulty of repairing

the "block" while the furnace is still hot, interchangeable blocks, which can be removed and replaced bodily by new "blocks," have been introduced at several works with good results. These blocks weigh from 9 to 10 tons, and are best handled by an overhead crane.

Water-cooling of the face of the arch between the gas and air ports has also been practised for some time in America, and is also being used in this country in the large Talbot furnaces. The latest device is to use bronze water-coolers, which, although more expensive, are said to give more satisfactory results; mild steel pipes of not less than 2 inches diameter, however,



(*Dimensions in Millimetres.*)

Fig. 122*a*.—Sectional Elevations, Plan, and Details of an Open Hearth Furnace "Block," with Bronze Water Coolers, in use at Gary Works, U.S.A.

give very good results, provided a very rapid flow of water is maintained, and every precaution taken to prevent any obstruction getting into the pipes. Fig. 122*a* shows the details of a "block" with bronze water-coolers in use at Gary Works in the United States.*

The Regenerators.—The regenerators, as will be seen from the sketch, are filled with checker brickwork, put in dry, arranged so that bricks and air spaces occur alternately. The best size for the regenerators for air and gas

* *Stahl und Eisen*, 1910, No. 2, and *Iron and Coal Trades Review*, February 18, 1910, p. 259.

is a somewhat disputed point, and must depend to some extent upon the conditions of working. In some furnaces the gas and air regenerators are made the same size, but it is far more usual to make the air the larger, and this is very much the better practice, as the temperature of the air has more influence on the perfect combustion of the gas than the temperature of the latter. There is, however, no great disadvantage in making gas and air of equal size, provided both are large enough, but sufficient regenerative surface is *most essential to economic working.* The mere cubic contents of regenerative chambers is by no means the only factor to be considered, the relation of the depth to the width or length being of greater importance; thus, shallow chambers, even when of greater capacity, may not be nearly so efficient as deeper chambers of less cubic contents. Mr. H. C. Macmillan considers that the chambers should never be less than 15 feet deep, preferably 20 feet for a large modern furnace, and this opinion was confirmed by other practical men in discussing his paper;* he further considers that the relative capacities of the gas and air regenerators should be in proportion of 1 to 1·37. The sketches given are from working drawings, and the student can from these calculate the dimensions of the regenerators in relation to the size of the furnace hearth or the capacity of the furnace, and make this a basis for the calculation of regenerative space for larger or smaller furnaces. In cases where the regenerators are of different sizes there may be a tendency for a large proportion of the waste products of combustion to flow down the one more than down the other on their way to the chimney, but if an excess is found to be passing down one, a few courses of bricks placed a little closer together at the top will generally effect a more equable distribution.

Messrs. Bone and Wheeler† have pointed out that changes according to the reversible reaction $CO + H_2O \rightleftharpoons CO_2 + H_2$ may take place during the passage of producer gas through the regenerator. Thus, during the passage of a gas containing steam, Hydrogen, and Oxides of Carbon through a regenerator whose highest temperature lies between 1,086° and 1,205° C., there will be a much greater tendency for the Carbon Dioxide and Hydrogen to react with the formation of Carbon Monoxide and water than for the reverse reaction to take place.

It therefore follows that a gas initially rich in Hydrogen and Carbon Dioxide will exhibit a marked disposition to change in the direction $CO_2 + H_2 \rightarrow CO + H_2O$, and Mr. J. H. Darby‡ has shown that the composition of gas from a Mond producer does change considerably on passing through the regenerators, thus—

	Entering the Regenerator.	Leaving the Regenerator.
	Per cent.	Per cent.
Carbon Dioxide, . . .	17·8	10·5
Carbon Monoxide, . . .	10·5	21·6
Hydrogen, ...	24·8	17·7

* *Proceed. Institute Cleveland Engineers*, January, 1903.
† *Iron and Steel Inst. Journ.*, 1908, vol. iii., p. 228.
‡ *Ibid.*, 1896, vol. i., pp. 1-26.

PLATE VIII.—Basic Open Hearth Furnace.

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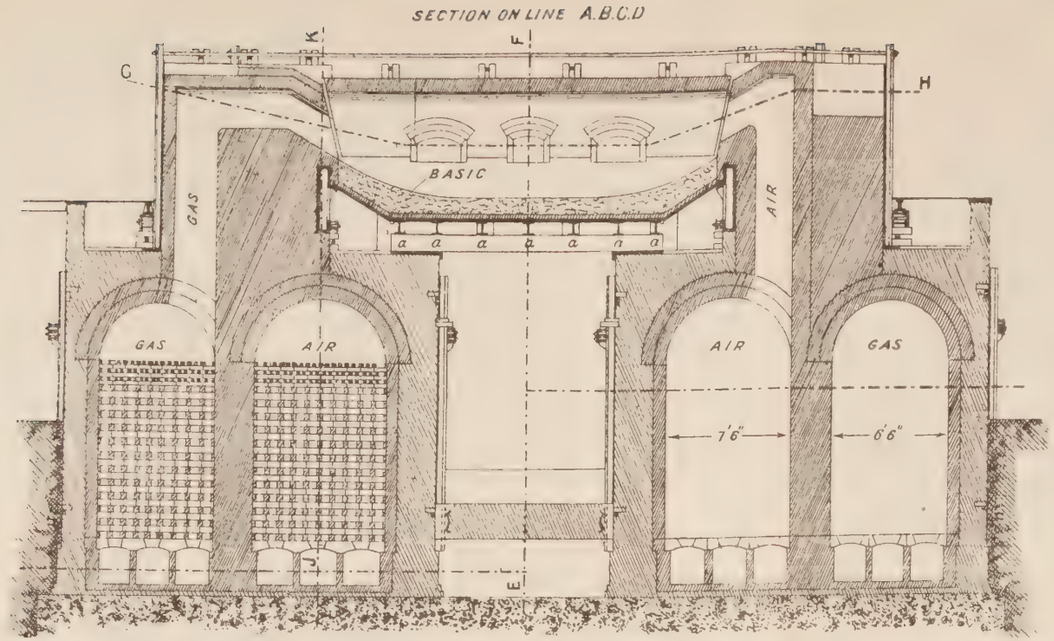


Fig. 123.

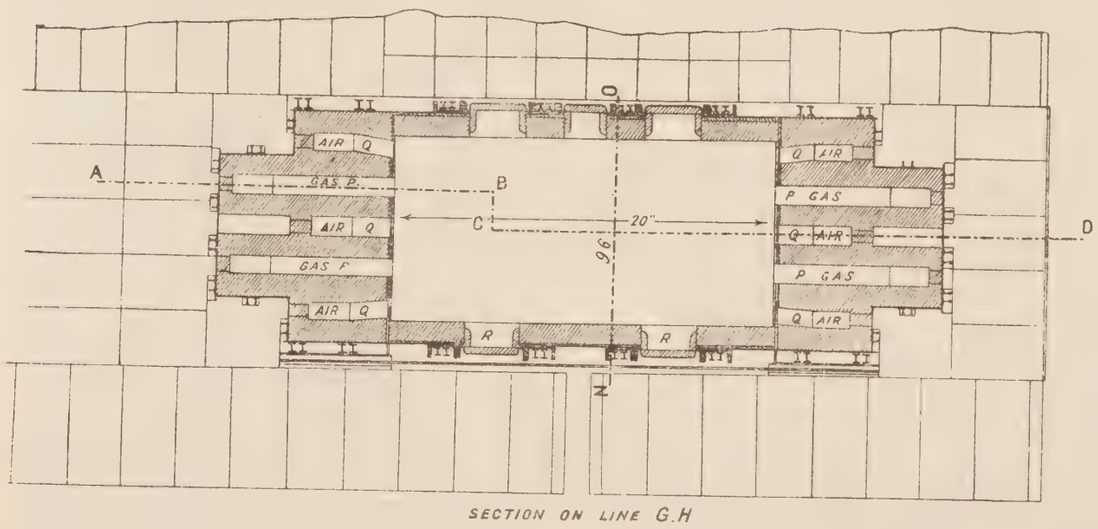


Fig. 124.

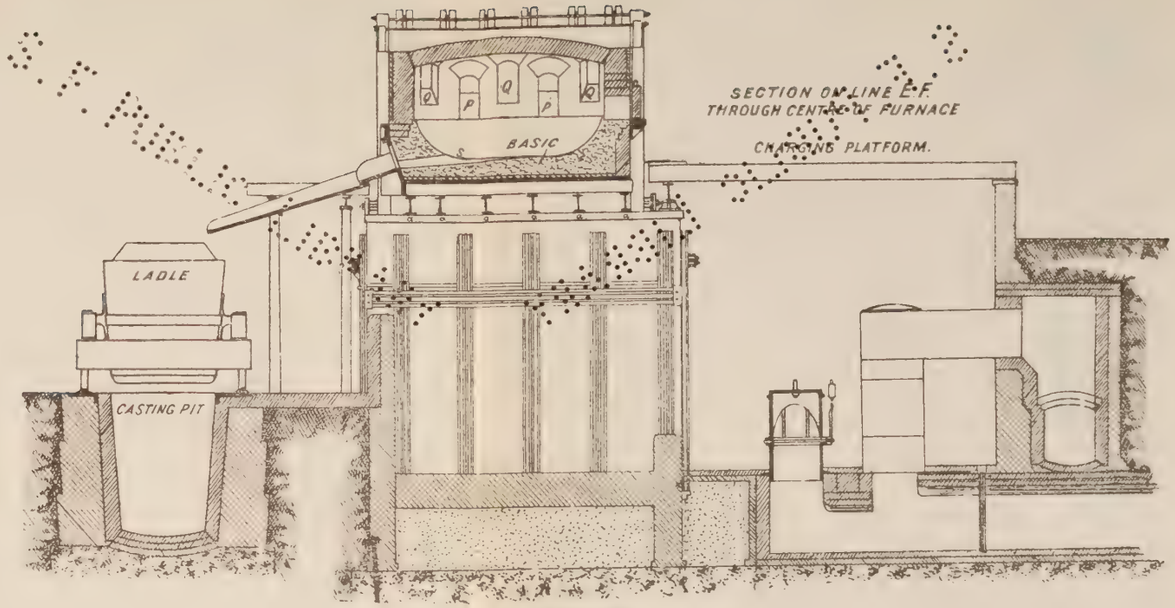


Fig. 125.

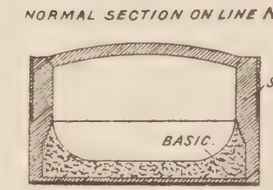


Fig. 124a.

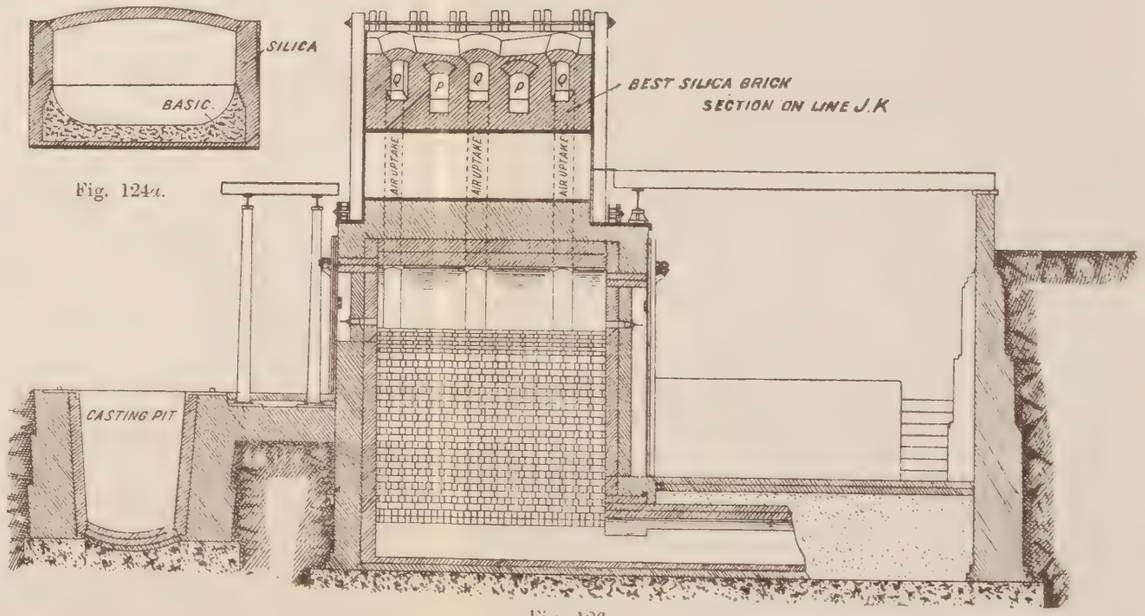


Fig. 126.

PLATE IX.—The Siemens Furnace.

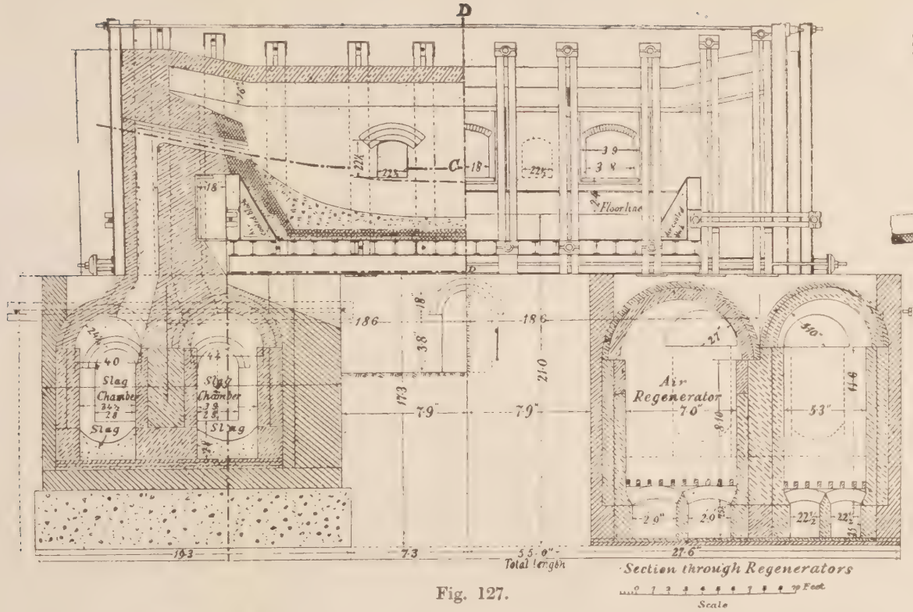


Fig. 127.

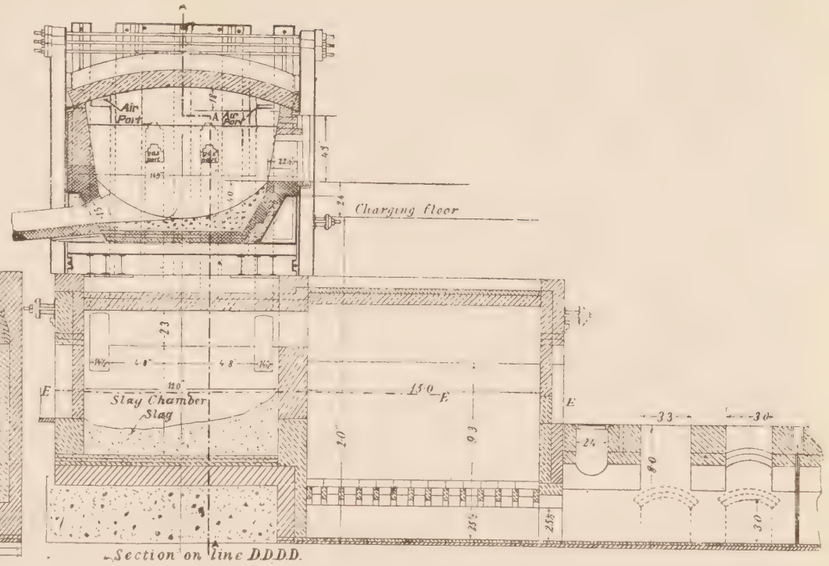


Fig. 129.

Modern 40-ton Basic Open-Hearth Furnace, showing dust catchers or slag chamber, and Talbot patent air-cooled hollow castings built into the "blocks."

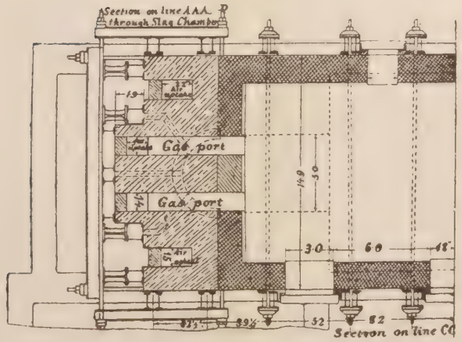


Fig. 128.

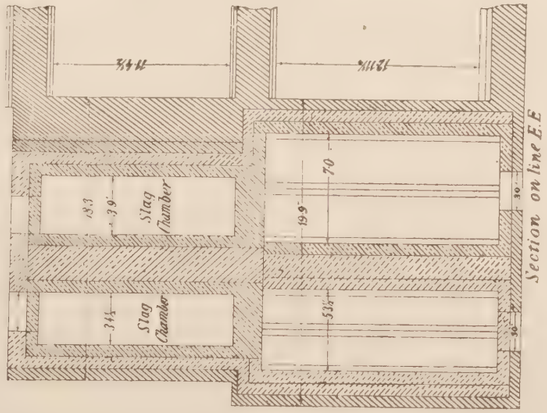


Fig. 130.

From figures given by Bone and Wheeler, it would appear that the gas obtained with a steam saturation temperature of 50° would undergo no change in passing through the regenerators. With gas obtained with a saturation temperature of 70° and more, there would be a marked tendency to increase the Carbon Monoxide and steam content at the expense of the Carbon Dioxide and Hydrogen in passing through the regenerators; while such a substitution of Carbon Monoxide for Hydrogen would be advantageous, the consequent large increase in the steam content would be detrimental from a furnace point of view.

Dust-Catchers.—In all open hearth practice a considerable amount of fine dust from the iron ore, or lime dust in the case of the basic process, is carried over mechanically with the gases, and often very seriously fluxes the regenerator bricks, causes them to run more or less together, and chokes the regenerators. To obviate this many furnaces are now built with a supplementary chamber between the ports and the regenerators to act as a slag and dust-catcher. By allowing the gas after leaving the furnace to pass into this dust-catcher, the greater part of the highly-heated dust particles is deposited before the gas reaches the regenerators, and in the event of slag from the furnace boiling over into the ports at any time, it is similarly prevented from reaching the regenerator brickwork.

In modern practice where very large furnaces of from 40 to 50 tons capacity are used, especially in basic practice, these dust-catchers are found to be an important detail in the construction of the furnace, as it is not merely a question of saving the brickwork in the regenerators, but the far more important one of increasing the length of time which a furnace can run before it has to be cooled down for repairs. Apart from this, directly the regenerators become more or less choked, the furnace begins to work sluggishly, with the result that a longer time is taken to work the charge, and there is also considerable danger of getting cold heats which may cause endless trouble and expense, so that any device that helps to keep them clear and prevent fluxing of the brickwork, even to a small extent, is an important matter. Figs. 127, 128, 129, and 130 (Plate ix.) are drawings of a modern 40-ton furnace, showing the dust-catcher or slag chamber.

The Tilting Furnace.—In America, of late years, furnaces built on rollers, or on rockers, have been used to some extent, so that the hearth section of the furnace can be tilted to enable the charge of finished steel to be poured into the ladle, thus avoiding the trouble of tapping. These furnaces probably offer greater advantages where the basic process is in operation than they do with the acid, as they enable a highly phosphoric or silicious slag to be poured off during the operation, and fresh slag to be formed by further additions. In the event of holes being formed in the bottom, the furnace can be tilted and more easily repaired than a fixed furnace, but one disadvantage of this type of furnace is, that if the bottom should be cut away under the taphole it is almost impossible to completely drain out the metal. The pouring hole, being above the level of the metal, is not rammed up with ganister, as in the ordinary furnace (Plate ix.), but a little sand is put loosely in, just sufficient to close the hole. The hole can be opened by merely pushing a bar through, without any sledging, and consequently all risks of hard taps are avoided, and the metal can be poured immediately it is ready. This latter is important in making steels of special grades, as if the metal is kept in the furnace owing to a hard taphole, after the required re-carburisation is reached, oxida-

tion is going on the whole time, and it frequently happens that the Carbon is reduced below the required limit. The tilting furnaces are more expensive to build than fixed furnaces of the same capacity, and taken all together for ordinary acid work, it seems somewhat doubtful if the advantages are so great as may appear at first sight.

The furnaces are divided into two types according to their method of tilting, one revolving on rollers about its own axis in the same way as the metal mixer shown on fig. 23, and the other tilting or rolling on rockers.

The Campbell Furnace.—This furnace is representative of the first type, and one designed by Mr. H. H. Campbell was put into operation in 1889, at the Pennsylvania Steel Company's Works. The furnace (figs. 131 and 132) revolves on its own axis, on four rings of rollers running on circular paths, and is rotated by a horizontal hydraulic cylinder, B. In

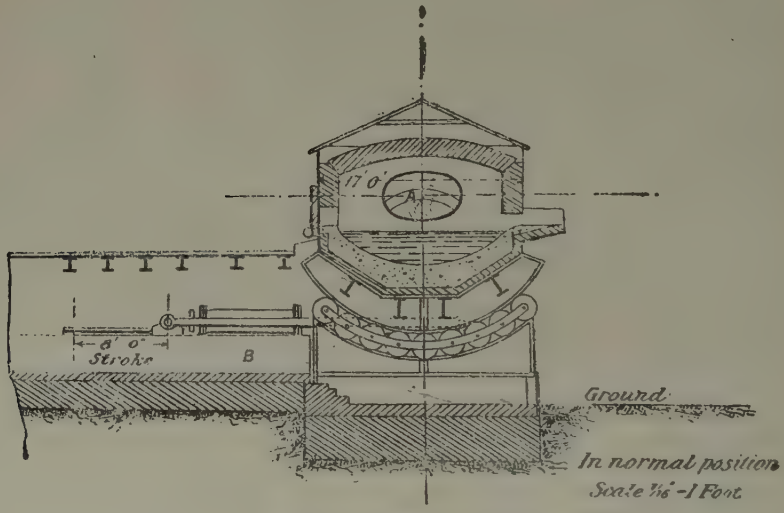


Fig. 131.—Campbell Furnace in normal position.

the movable section of the furnace at each end is an oval opening, A, opposite the fixed gas and air ports, and to allow this portion of the furnace to move freely, a space of about half an inch is left between the furnace ends and the fixed ports. Both ports and furnace ends are faced with water-cooled cast-iron plates, and the block forming the ports is enclosed in an iron framework, so arranged that the whole can be changed when repairs are necessary. This latter detail is due to Mr. C. E. Stafford, of Pittsburg.

When the furnace is tilted the air ports are partially closed. Molten blast furnace metal is now being used in these furnaces with considerable increase in output, and without, it is stated, appreciably increasing the wear and tear on the furnace bottom. In charging cold pig-iron the furnace is usually tilted, and the half pigs are shot in from a shoot which severely tries the bottom. The furnace can be charged by hand or by a Wellman charging machine (fig. 147). At the Pennsylvania Steel

Company's Works horizontal regenerative chambers are used, and air is blown into the chambers by an electrically-driven fan.

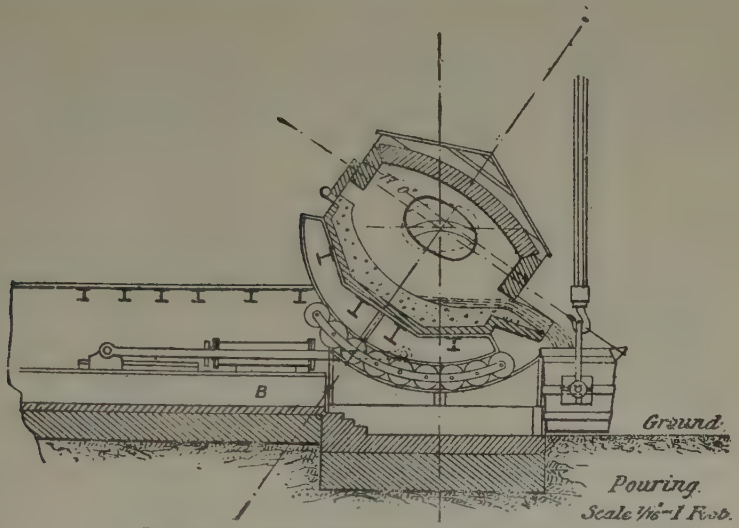
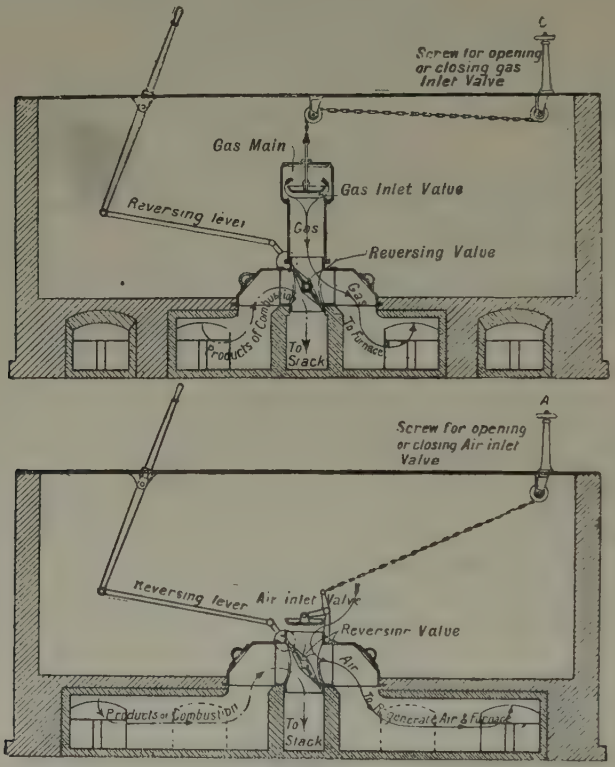


Fig. 132.—Campbell Furnace, position when pouring.
B, Hydraulic tilting cylinder.

The Wellman Furnace.—This furnace (figs. 133 and 134) is similar in general construction to the Campbell furnace, but instead of revolving about its own axis it is mounted on rockers, and can be tilted to any required angle for pouring by means of the vertical hydraulic cylinder shown in fig. 134, Plate x. In the latest form of furnace the ports are encased in a metal cage, mounted on wheels running on rails, which enable it to be moved a few inches towards or from the end of the furnace. The two passages leading from the regenerative chambers to the ports terminate in water troughs about on the level of the charging floor, and these latter are so designed as to allow a small motion of the port without breaking the seal. When pouring is about to commence the ports are moved away to enable the furnace to tilt freely, and when the operation is over they are moved back into contact with the furnace. During pouring the port ends of the furnace open to the air are larger than in the Campbell furnace, thus admitting more air into the furnace. Both the Campbell and Wellman furnaces are doing good work, but the latter is somewhat cheaper to build.

Valves.—There are two kinds of valves used in connection with Siemens furnaces, the inlet valves for regulating the admission of air and gas, and the reversing valves for controlling the direction of the air and gas, and the products of combustion. The former are usually the simple mushroom form, shown in figs. 135 and 135*a*, marked air and gas inlet valve respectively, and require no special description; but the reversing valves vary very considerably in design, and have to be most carefully constructed if they are to do their work efficiently. In the case of the gas-reversing valve, it is exposed to the hot incoming gases from the producer on the one side, and the escaping hot products of combustion on the other, and it is not an easy matter to devise a valve which will work gastight over a considerable

period of time under these conditions. The old form of "butterfly valve" shown in position in figs. 135 and 135*a*, and marked reversing valve, has done excellent service, and is still very largely used, but with the greatest care is liable to warp and become leaky. When this occurs, the condition of the valve rapidly becomes worse owing to the leaking gas burning at the valve seat, and it is practically impossible to repair the valve without removing it. The construction of the valve is very simple ; it consists of a cast-iron flap, supported at its centre on a trunnion or spindle, so that by means of levers it can be swung over at will from one side to the other.



Figs. 135 and 135*a*.—Sketch showing general arrangement of inlet and reversing valves of Siemens furnace. The latter are of the "Butterfly" type, one for gas and one for air, and are reversed by the levers shown.

Figs. 136 and 136*a* give on a large scale plan and sectional elevation of this form of valve, and show it in the reverse position to figs. 135 and 135*a*, and from the table attached detailed dimensions of valves from 15 inches to 36 inches can be obtained. A modification of this valve, patented by Mr. William Kirkham, of Sheffield, is shown in figs. 137 and 138, in which the valve flap is made in two parts, *a* and *b*, the bottom portion, *b*, with the trunnion, *c*, being cast in one piece, and the top portion, *a*, having a deep groove cast in its thicker end of such a width that it rides or clips on the trunnion of the lower portion. By this arrangement, although the entire valve moves as one piece when reversed by the lever, by allowing a little play between the two connecting parts of the valve, the respective parts

PLATE X.—50-Ton Wellman Open Hearth Tipping Furnace.

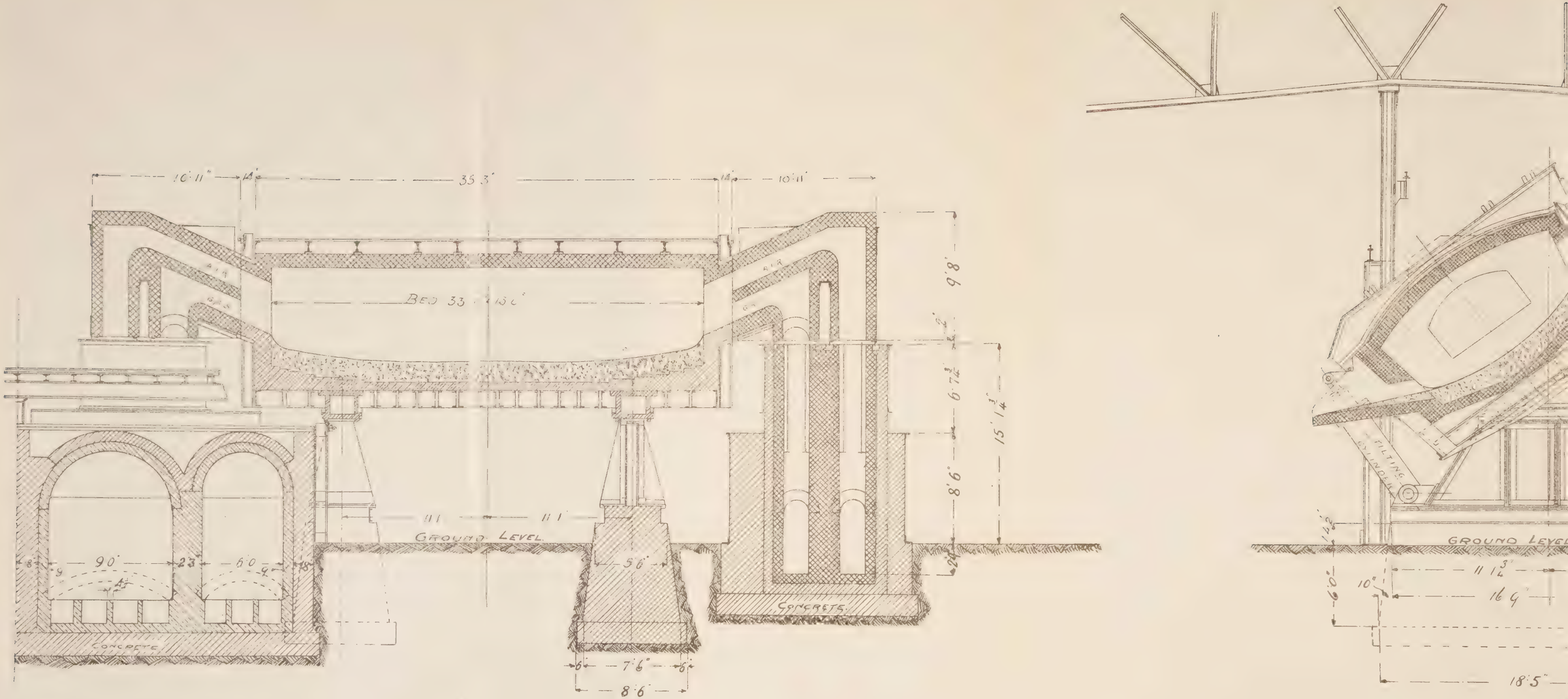


Fig. 133.

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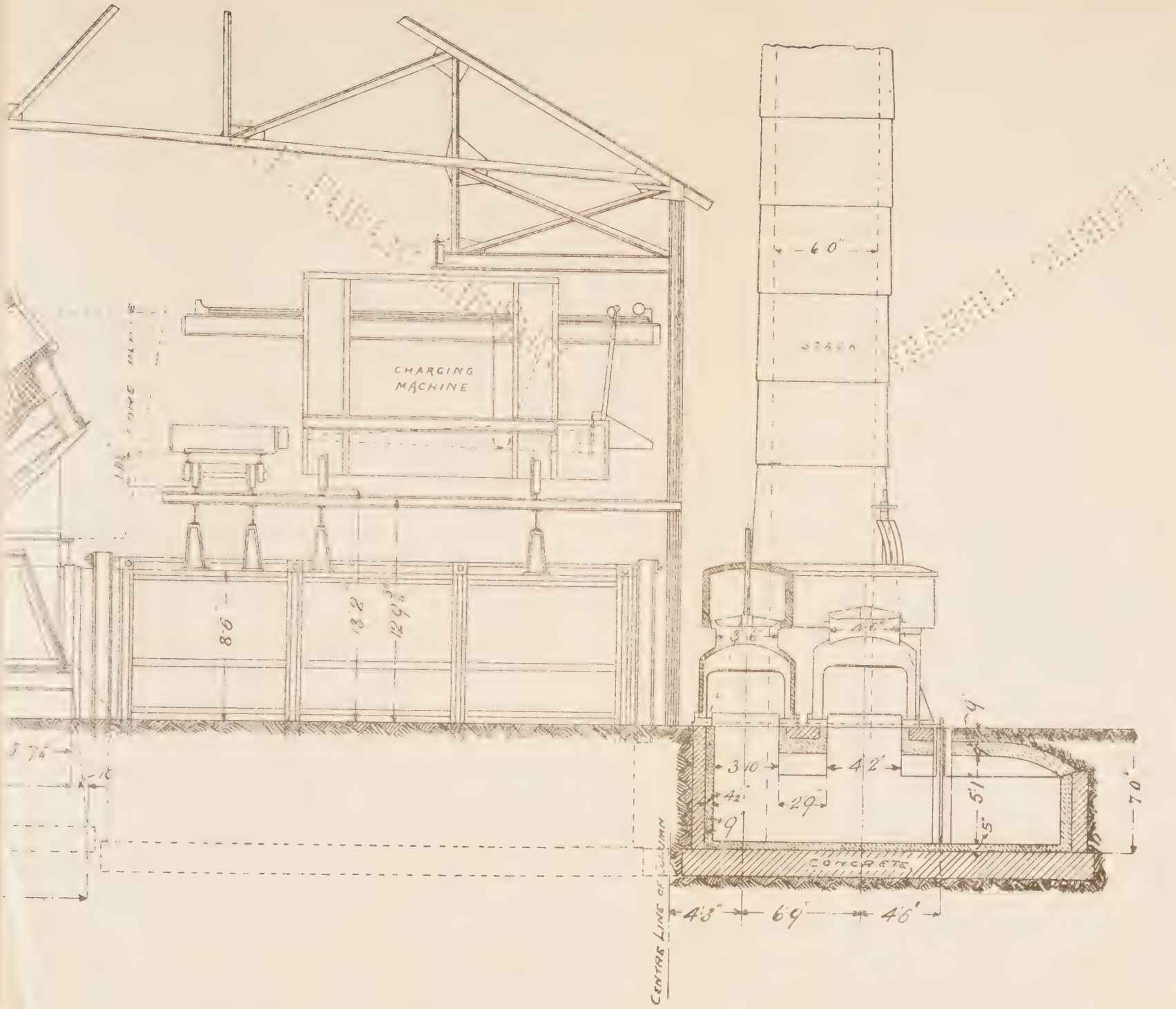
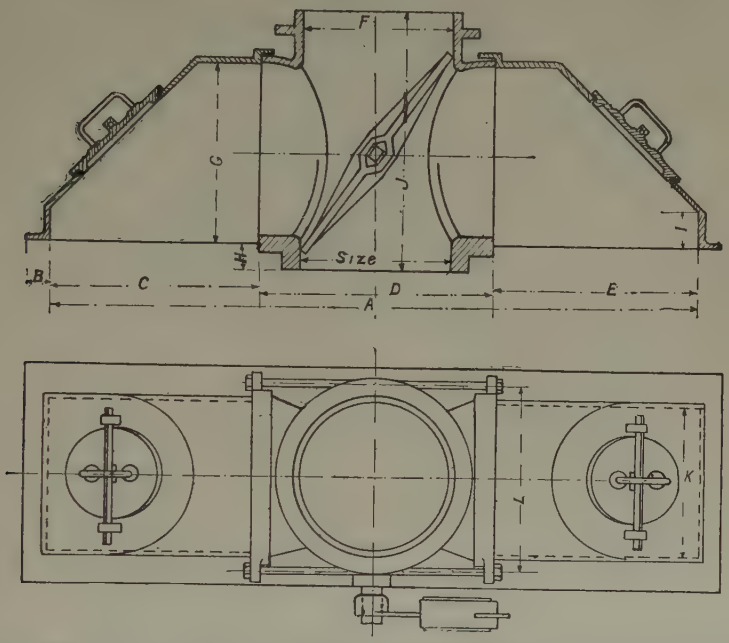


Fig. 134.

will bed better on their faces, and become less affected by warping and distortion than when the valve is one rigid piece. The author has received very satisfactory reports from several people who are using this valve.



Figs. 136 and 136*a*.—Plan and Sectional Elevation of Butterfly Reversing Valve.

DIMENSIONS OF VALVES.

Size.	A	B	C	D	E	F	G	H	I	J	K	L
ins.	ft. ins.	ins.	ft. ins.	ft. ins.	ft. ins.	ins.	ft. ins.	ins.	ins.	ft. ins.	ft. ins.	ft. ins.
15	5 11½	2¾	1 11	2 1½	1 11	15	1 6⅜	3½	2	2 5	1 3	1 8
18	6 7	3	2 1	2 5	2 1	18	1 10⅛	3½	2	2 9¼	1 6	1 11½
21	8 1¾	3	2 8⅞	2 8	2 8⅞	21	2 0⅝	3½	2	3 0	1 9	2 2
22½	8 2	3	2 8½	2 9	2 8½	22½	2 2½	3½	4½	3 3	1 10½	2 3¾
24	8 4¼	3	2 8½	2 11¼	2 8½	24	2 3⅞	3½	5	3 5	2 0	2 5⅜
25⅓	8 8	3½	2 10	3 0	2 10	25½	2 6	3¼	7⅞	3 7	2 1½	2 7
27	9 3¾	3 5/16	3 0½	3 2¾	3 0½	27	2 7	3¾	5	3 8¼	2 3	2 9
30	9 10¼	3½	3 2½	3 6¼	3 2	30	2 10	4½	6	4 1¼	2 6	3 0½
33	11 3	4	3 9	3 9	3 9	33	3 2⅞	4	9¼	4 6⅛	2 9	3 2½
36	12 2	4	4 0	4 2	4 0	36	3 5⅞	4¾	9¼	4 9¼	3 0	3 5⅞

A valve largely used in America is shown in fig. 139. It consists of a thick hollow disc, the periphery of which is formed to a double bevel. Two valves are connected to one rocking lever, so that when one is raised the other is lowered, and one valve is always resting on the bottom seat, and the other against the upper seat, when at the end of its range. The special shape of the valve gives great stiffness, and reduces the danger of leakage through warping. Two pairs of valves are required—one to control the gas, and one the air.

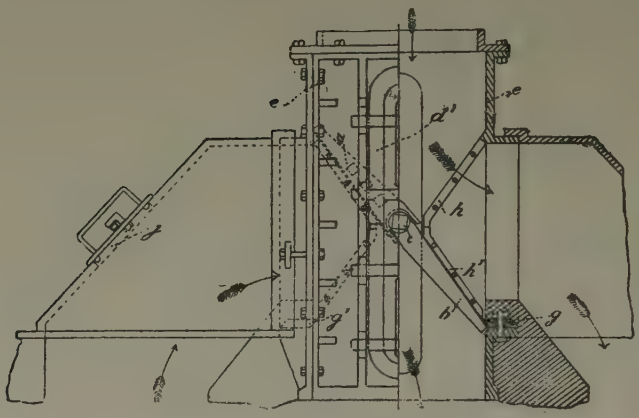


Fig. 137.—Kirkham Modified Butterfly Valve.

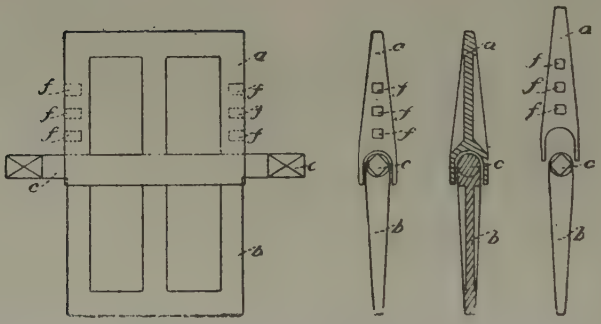


Fig. 138.—Details of Kirkham Valve—*f*, Holes for inserting bar to assist in removing flap, *a*, for repairs; *g*, removable valve seat which can be replaced when worn.

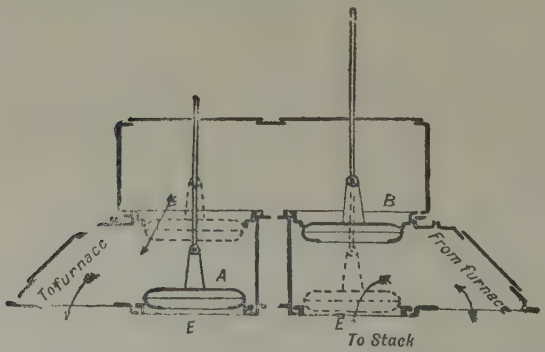


Fig. 139.—Hollow Disc Reversing Valve. Position, A, open to regenerators and furnace; position, B, products of combustion passing from furnace to the stack.

The last form of valve, although an improvement on the ordinary "pot-lid" flat valve hung on opposite ends of a rocking lever, is open to the same objection, that both valves are never closed simultaneously, any difference in temperature of any of the parts causing one or other valve to tend to leave its seat, and thus establish a leak, which rapidly grows worse owing to the gases burning, and may cause considerable damage to the gas valve before it is discovered by the furnaceman.

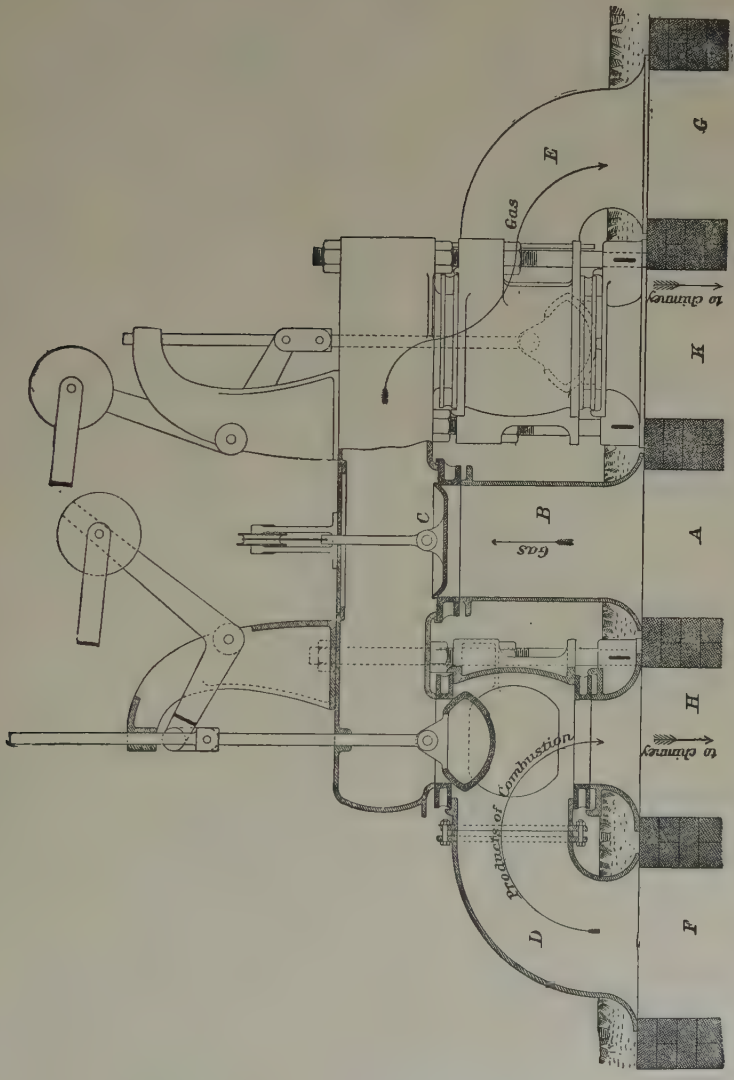


Fig. 140.—The Hall Valve.

On raising the gas inlet valve, C, the gas passes from B to the regenerators and furnace above the valve on the right hand through E and G, and the products of combustion from the furnace pass from F and D underneath the valve on the left hand through H to the stack, as shown by the arrows.

The valve (fig. 140) fitted by Mr. John W. Hall of Birmingham to furnaces of his construction removes this objection. The two valves are entirely independent of each other, each being reversed by its own lever, and the preponderance of the valves and weighted levers is so arranged that

the valves come to their seats with a sharp blow, and are held in contact with both the upper and lower seats by gravity. The blow not only enables the valve and seat to come together in spite of any soot present on them, but assures the furnaceman that the valve is properly home. The steel valves are hollow and contain no ribs, so that they are free to expand equally in all directions, and do not change their shape when heated. Their faces are turned to form an arc of a circle, so that the valves will fit the seats with mathematical precision when canted to very considerable angles, and being attached to the spindle, which is a very free fit, find their own position on the seats even if the spindles should be considerably out of centre with the seats. The cast-steel seats, which are reversible, and can be turned over when worn, are kept cool by contact with the external air, and by turning the nuts which hold the parts of the boxes together so as to lift the box a small distance, a seat can be removed and a new one put in from the outside while the furnace is working if the seat is at the bottom, and by shutting off the gas for less than two minutes if the seat is at the top. Some of these valves and seats have run for four years without any sign of wear, probably owing to the fact that leakage has never occurred.

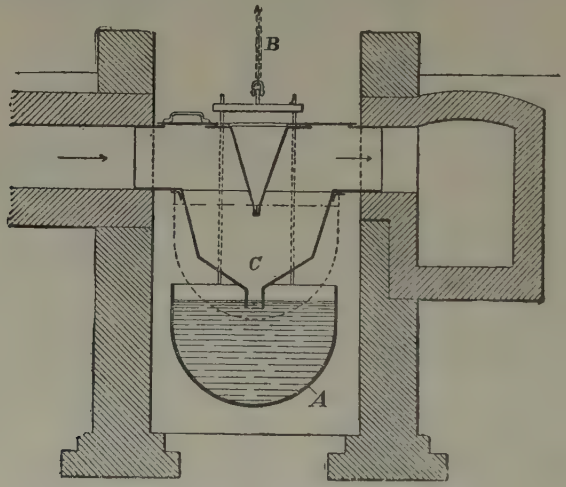


Fig. 141 —Wailes Siphon Reversing Valve.

Below is a cup of water, A, which is kept full, and can be raised or lowered by chain, B, and into this dips a funnel, C. In the position shown in the sketch any gas is prevented from escaping from the funnel-shaped orifice, but can pass along the flue, as shown by the arrows. When the cup of water, A, is raised into the position shown by the dotted lines, so that the V-shaped mid-feather dips below the surface of the water, the flow of gas is prevented altogether. This valve has been used experimentally in several works in England, but has not been generally adopted.

The gas enters from the gas flue, A (fig. 140), through the centre pipe, B, and passes through the regulating valve, C, to the reversing valves on each side. The bend pipes, D and E, lead the gases to or from the brick flues, F and G, which are in connection with the regenerators, while the waste gases pass through the base castings to the chimney flues, H and K. The arrows show the directions of the currents. If the regulator valve shown in the figure were raised, the gas would enter the regenerator on the right, and the waste gases would leave that on the left.

Some years ago a water-cooled valve, called the siphon valve (shown in fig. 141), was introduced by the late Mr. Wailes, formerly manager of the

Patent Shaft and Axle-tree Company. From the sketch it will be seen that it consisted of a cup which was kept full of water, which could be raised or lowered at will to form a water seal. Another water-seal valve, designed by Mr. Wailes, is shown in fig. 142, and this, and modifications of it, have been largely used. The arrangement will be readily understood by referring to the sketch and description.

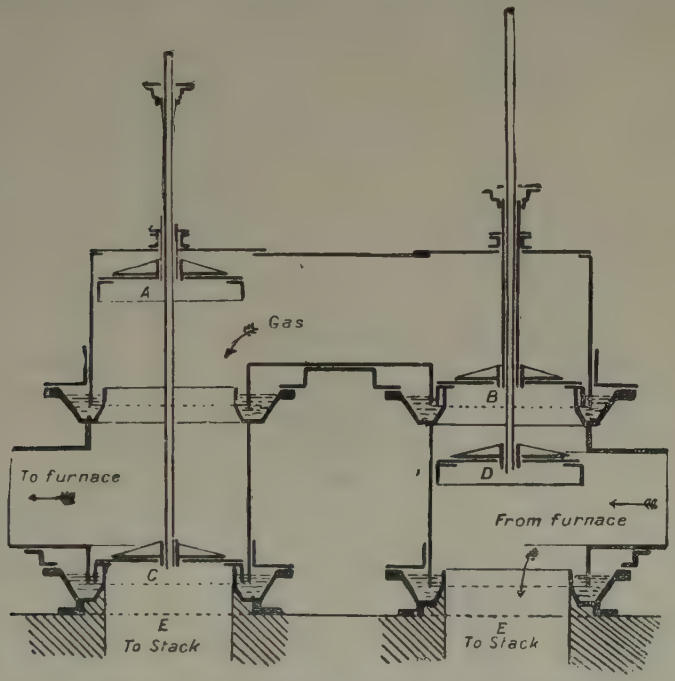


Fig. 142.—The Wailes Water-Seal Reversing Valve.

There are two valves on the same rod, but having independent motion, the top one being attached to a sleeve and the bottom one to the rod. When the valves are lowered the peripheries dip into the troughs of water shown, which are kept full of running water. When the valves are in position, A and C, the gas is passing to the regenerators and the furnace; and when in position of B and D, the gas valve, B, dips into the water seal, and the products of combustion pass from the regenerators under D through E to the stack. The valve, D, is largely protected from hot gases by being raised into a recess between the two valves. The reversal of position of valves reverses the direction of the gas. There are similar sets of valves on each furnace to control the direction of the air.

Another form of water-cooled valve is that patented by Mr. F. Mills (shown in fig. 143). In this valve a stream of water is constantly flowing down the stalk of the valve, which is made hollow, and the valve is of such a section that it is always water cooled, whether at the top or bottom of its range. The details of the design will be seen from the sketch.

The Chimney.—For the efficient working of a furnace nothing is of greater importance than a good draught, and each furnace should have a *separate* stack of such a size that a strong draught can always be insured, even when a furnace is in bad condition. It is always easy to damper a chimney if it is pulling too strongly, but it is impossible to increase the pull above the point limited by its dimensions, and hence the importance of

having a chimney of such a size that it is rather above than below the ordinary requirements.

Position of Producer.—The position of the producer in relation to its distance from the furnace is still a disputed point, but the tendency in modern practice is to place the producer as near as possible to the furnace, with the double object of losing as little as possible of the sensible heat of the gas, and also of preventing the condensation of the volatile Hydro carbons. The advantage of introducing very hot gas from the producer, may, so far as the economy of fuel is concerned, be regarded as nil, as,

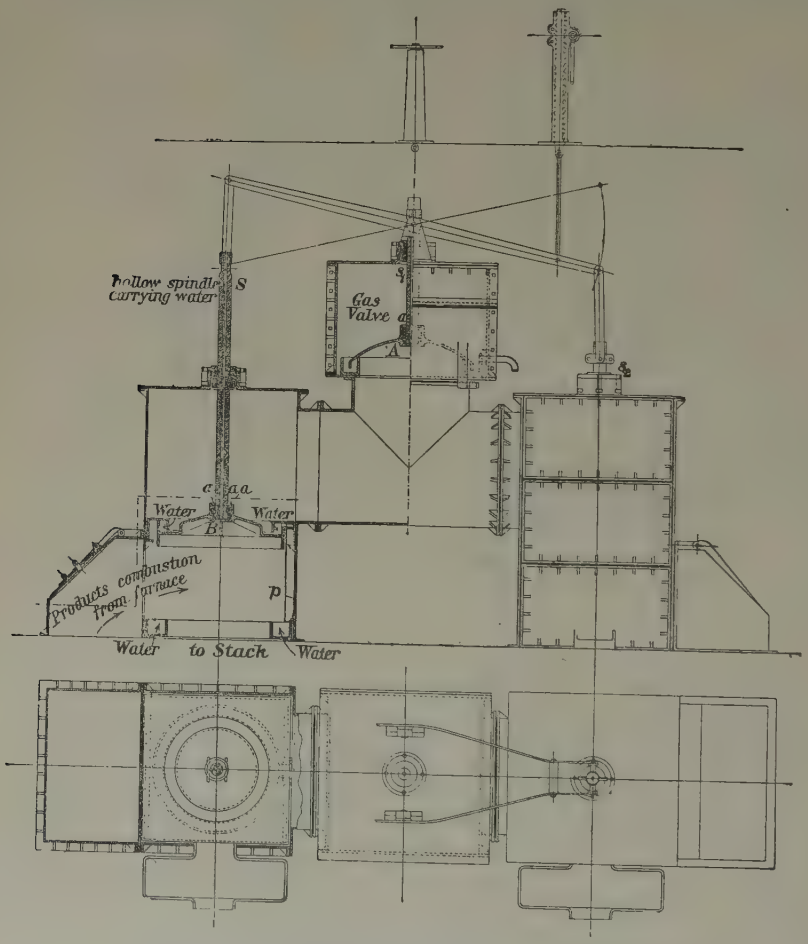


Fig. 143.—The Mills Water-cooled Gas Reversing Valve.

A is gas inlet valve; B, one of the reversing valves. When the valve, B, is in position shown, no gas can pass to furnace, but products of combustion are passing from the furnace underneath it to the stack, and the gas from the producer when gas valve, A, is open passes above a similar valve on the right to the furnace. The valves are on one rocking lever, pivotted at centre, so that raising one valve lowers the other. S, S_1, and S_2 are hollow spindles through which water is admitted, and flows out through holes, a, a, a, over the valve; P is a passage by which overflow water runs from the valve to the lower seat, and thence by a pipe to the cooling pond.

assuming that it is hotter than the cool end of the regenerator where it enters, it raises the checker brickwork to its own temperature, and when the valves are reversed, and the products of combustion pass through this regenerator, these gases are heated up to the same temperature as the temperature of the producer gas on entering, and consequently carry away to the stack as much heat as the latter originally introduced. To this must be added the very serious difficulty of maintaining the valves gastight, when very hot gas is used, although this risk is greatly reduced by using a good type of modern water-cooled valve. The calorific value of the Hydrocarbons has also, in all probability, been over-estimated, as these are largely dissociated when they come into contact with the hot surfaces of the regenerators, soot being deposited, and causing much trouble.

On the other hand, although no direct economy in fuel may result by taking very hot gas into the regenerators, there is no doubt the furnace works more rapidly when this is done, as, the chimney end of the regenerators being much hotter, the draught in the stack is increased, a steady flame is maintained, and rapid combustion takes place in the furnace, whereby the output may be considerably increased. All practical men know the difference between working a furnace in which the gas and air are drawn rapidly into the furnace hearth, and one in which the air and gas enter slowly; and in the opinion of some practical men, it pays to maintain these conditions for rapid working by allowing a certain proportion of unabsorbed heat to pass away to the stack. One steel works manager, of very large experience, informs the author that he always, as far as possible, maintains the temperature of his stack at 1000° F., and finds it more economical to do so when output and other practical points are considered, than to reduce the temperature to 500° or 600° F., although, theoretically, there should be no advantage when the temperature is maintained above 700° F. Against this it may be argued that if this is the only reason for taking very hot gas from the producer, it would be far better to obtain the quick working by building a larger stack in the first place; but those who favour the employment of hot gases from the producer contend that this does not give the same satisfactory results. The usual practice to-day is to place the producers from 30 to 50 yards from the furnace, and if the gas is carried through a brick-lined tube or culvert, there is very little sensible heat lost in travelling that distance, and at the same time a certain proportion of the less volatile Hydrocarbons are condensed before the gases enter the regenerators. The new form of Siemens furnace, which is fully described in the chapter on reheating furnaces, is also being used for steel melting, and is an extreme case of the producer being so close to the furnace that it forms a part of the furnace itself, and there can be no doubt that it largely owes its success to the fact that the gases are delivered into the furnace direct from the producer at a very high temperature, thus rendering it unnecessary to regenerate the gas at all. The extreme on the other side was the original arrangement of cooling tube used with the Siemens producer, in which the gases were purposely cooled down as much as possible before entering the furnace. This latter arrangement is never used now.

Drying the Furnace.—Before putting in the hearth of the furnace, it is most essential that the whole structure should be very thoroughly dried. This is best done by lighting a good fire in each of the four regenerators before the checker brickwork is built in, and keeping it burning for about two days and nights, allowing the hot air and smoke to pass up into the furnace. These fires should then be removed, the checker bricks put into the regenerators, and built up dry, and a good coke fire lit in the body of the furnace, the valves being kept open to allow all the products of combustion to pass to the stack through all four regenerators at the

same time. In starting this fire it will generally be necessary to light a pilot fire in the chimney to create a draught, and the furnace fire should be maintained for four or five days before the furnace doors are entirely closed, and gas from the producer put into the furnace. It is advisable also to dry all flues by means of fires near each manhole, previous to starting the fire in the furnace itself. Before turning the gas into the furnace, a clear bright fire should be made at each end of the hearth near the gas ports, and before opening the gas valve leading to the furnace, the producer gas should be allowed to pass for a considerable time through the flues, and out at the manhole *furthest* from the producers to sweep all the air out of the flues. After the gas has been passing for some time it should be tested by lighting at the manhole, and when it burns steadily for some minutes without going out, the manhole may be luted up, and gas passed into the furnace, care being taken that the air inlet valves are closed, and kept so. Sometimes a slight explosion occurs when the gas first enters the furnace, which may possibly extinguish the fires inside, in which case the gas must be shut off and the fires re-lit, the producer gas being allowed to burn at the manhole meanwhile. Instead of testing the gas by burning at the manhole, when it is found to burn well at the producer, if all the valves be left open to the stack, and the gas be drawn through the flues for from 10 to 15 minutes, and allowed to escape at the chimney, this will sweep all air out of the flues, and it will then be quite safe to turn the gas into the furnace. The gas should be allowed to burn in the furnace for a few hours with air admitted through the furnace *doors*, and the air valves opened to a very small extent. The valves should not be reversed for the first two or three hours, and when they have to be reversed, a most important point to bear in mind is *always to reverse* the gas valve first, and, a few seconds after, the air valve. After running for two to three hours in each direction as above, the reversals may take place at more frequent intervals, the time being gradually reduced, until reversals take place every twenty minutes.

The Furnace Lining.—So far as we have gone at present, speaking generally, the details of construction and preparation of the furnace for work apply equally to the acid and basic processes. We now come to the lining of the bottom or hearth of the furnace, and, as it is this lining which forms the vital difference between the two processes, we shall describe each process separately.

THE ACID OPEN HEARTH PROCESS.

The furnace, having been dried as described, is now ready to have the bottom or hearth proper made, which is done as follows :—

Making Hearth and Tapping-Hole.—Fig. 144 represents a longitudinal section showing courses of Silica bricks on the bottom plates, and others built in steps from the side walls. The bottom is made by fritting on the purest Silica sand, and this stepped arrangement of Silica bricks at the sides is to assist in forming the banks of the hearth, as otherwise a much greater thickness of sand would have to be glazed on at the sides compared with the central part of the hearth.

In the centre of the tapping side of the furnace it is usual to leave a hole in the brickwork arched over, about 18 inches square, and before starting to frit on the sand bottom, a taper plug, usually of iron, and varying in diameter in proportion to the size of the furnace, is inserted from the outside, passing quite into the furnace, and is then well rammed round with ground ganister. When the ganister has set firmly, the plug is withdrawn from the outside, and the tapping-hole filled with lumps of

anthracite from the inside of the furnace, by pushing it in with a tool called a rabble. The rabble is shown in sketch, fig. 155, p. 167, and the end is held against the inside of the tapping-hole, while fireclay is rammed in from the outside. In the transverse section of the furnace, in Plate viii., fig. 125, are shown the shape and position of the tap-hole. The glazing on of the Silica sand bottom can then be proceeded with. Before putting in any sand it is desirable, if possible, to spread sandstone or granite chippings previously thoroughly dried and heated in a sand furnace, as evenly over the bottom as possible, and to urge the heat of the furnace by reversing the valves every twenty minutes until the chippings are fritted or fused on to the Silica bricks covering the bottom iron plates. When these chippings begin to soften, the best Silica sand is thrown into the furnace, and spread evenly over the bottom to a depth of half an inch, with a large flat-ended iron known as a broad hook, shown in sketch, fig. 155. This is then thoroughly glazed on, when another half inch of sand is added and glazed, and so on, until the bottom and banks of the furnace are of the required thickness and shape.

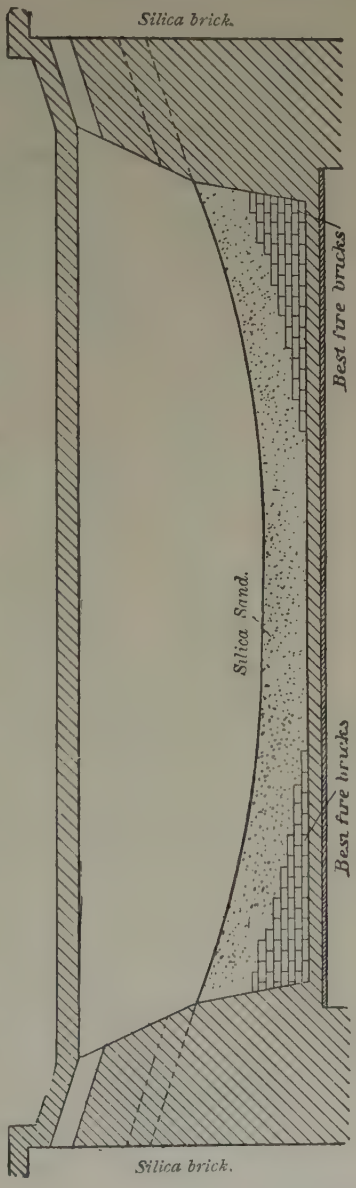
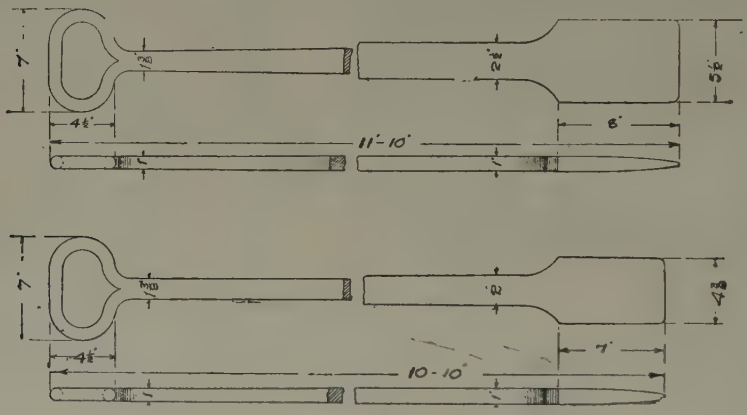


Fig. 144.—Section through Hearth of Siemens Acid Furnace.

Charging and Starting the Furnace.—In starting an acid furnace, it is customary to have what is called a "wash out" heat to thoroughly solidify the bottom. This consists in melting a small charge—say about $\frac{1}{6}$ of a full charge of pig-iron—and adding some silicious material like old red brick ends or slag from previous charges to form a fluid slag. When melted, this is well rabbled or raked about to wash the banks of the furnace, and then the charge is tapped out and taken to the scrap heap. Instead of using a small pig charge, the common custom in America is to melt a charge of acid open hearth slag in the furnace, and thoroughly wash the banks with this before charging any metal. The next three or four heats should be small ones, and should consist principally of pig-iron with a little scrap, the charge both in weight and proportion of scrap being gradually increased until the furnace is in good working order.

The proportion of scrap to pig-iron worked in a Siemens furnace will vary with local conditions, such as the quality of the pig, and the quantity of scrap available in the district, but the usual practice in this country is to use about 70 to 80 per cent. pig and 20 to 30 per cent. steel scrap. Good heavy scrap, such as bar or rail crop ends, is much to be preferred to light scrap, not only on account of the ease with which it can be handled, but also on account of less liability to oxidation during the melting. With very light scrap it is often impossible to get the full proportion into the furnace at starting, and it has to be added from time to time as the charge melts. Care should be taken to keep light scrap off the bottom and banks of the furnace, as the Oxide of Iron which forms rapidly cuts the furnace hearth away. For convenience in charging pig-iron is usually broken into half pigs, and these, in this country, are generally charged by hand, through the furnace doors with the "peel" (figs. 145 and 146), by means of which a good furnaceman will distribute his charge evenly over the entire hearth. The furnaceman rests the "peel" on the jamb of the door-way, thus getting a good leverage, another man places a

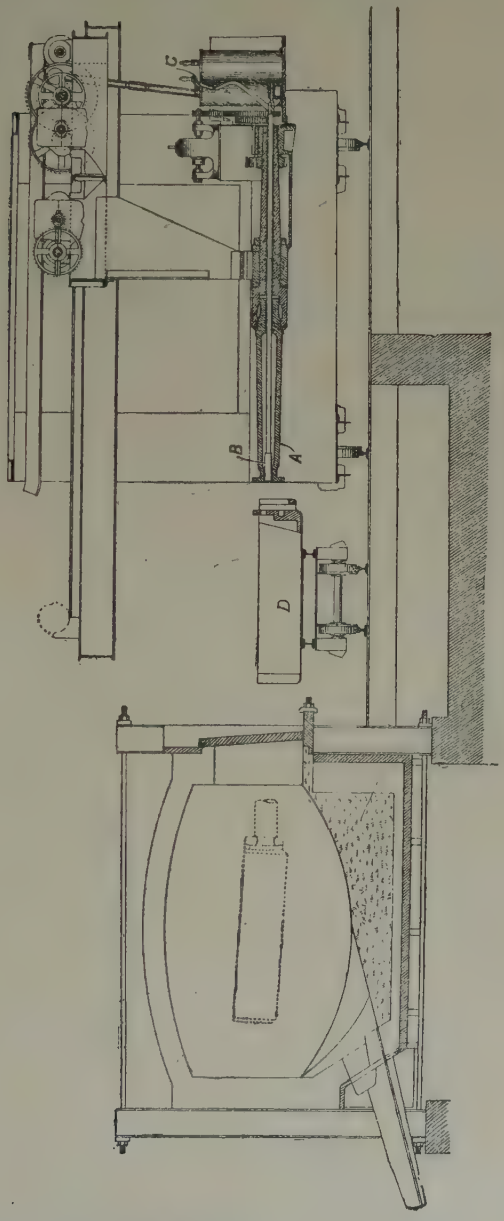


Figs. 145 and 146.—Peels for Siemens Furnace.

half pig upon its flat end, and he is able to shoot it into any part of the furnace he desires. To save time, especially in large furnaces, the charging is done through two or three doors at the same time by men working with a peel at each. After the pig-iron is in the furnace, the scrap is placed on the top, the furnace closed, and the gas turned in, and in from three to four hours the charge will be melted. The almost universal practice in this country is to charge the pig-iron first on the bottom of the furnace, and the scrap afterwards, the prevalent opinion being that scrap rapidly cuts away the bottom. This probably is so in the case of *very light scrap* which quickly oxidises, but this action, in the case of heavy scrap, is comparatively slight, as may be gathered from the results of American practice, where, in some works, it is the custom to charge the scrap before the pig-iron. In some experiments made at one of the large works in this country to test this point, practically no difference was found as regards wear and tear on the bottom when fairly heavy scrap was used.

Mechanical Chargers.—One of the most serious drawbacks to the open hearth process is the time lost in charging, especially in the case of very large furnaces, and to obviate this, numerous machines have been

devised. Fig. 147 shows a Wellman charging machine, which is largely used in America, in this country, and on the Continent.



WELLMAN ELECTRIC OPEN HEARTH CHARGING MACHINE

LONGITUDINAL CROSS SECTION

Fig. 147.—A, Hollow charging bar; B, locking bar; C, lever for actuating locking bar; D, charging box.

The Wellman Charging Machine.—In this machine the materials are charged in boxes holding about 1 ton, the boxes being picked up by the machine, pushed into the furnace, turned upside down to empty, and with-

drawn. The boxes already loaded are brought up on a bogie running on rails, to the charging doors of the furnace, and the charger will pick up and empty one every minute, so that a 50-ton furnace can be charged in about an hour, provided the machine is kept supplied with loaded boxes. Fig. 147 shows a cross-section of the furnace, the charging bogie, and

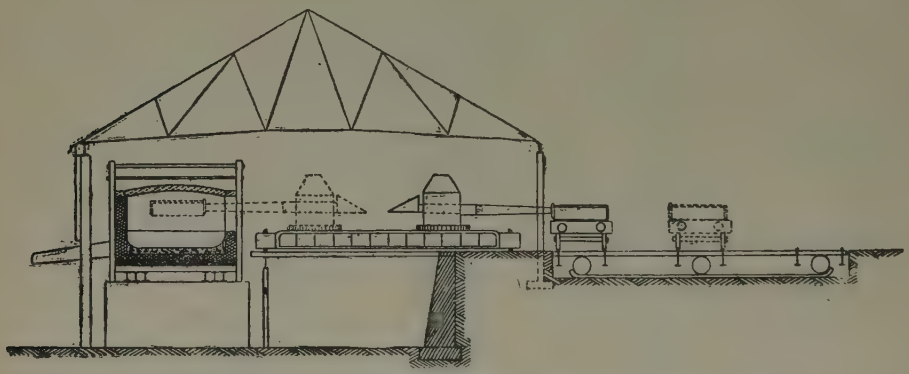


Fig. 148.—Low Ground Wellman-Seaver Charging Machine, with Slewing Motion.

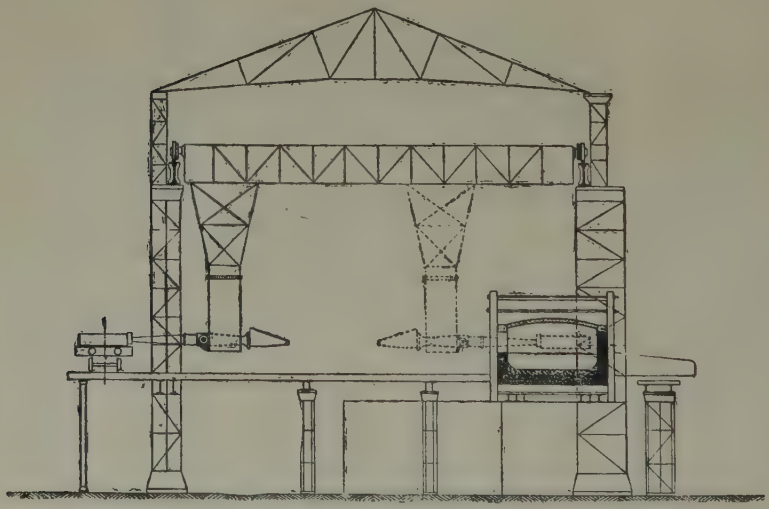


Fig. 149.—Overhead Wellman-Seaver Charging Machine, with Slewing Motion.

charging machine itself. The bogie usually carries three or four boxes. In operating the machine, the end of the charging bar is brought forward and dropped into a socket on the end of the charging box, and this is then locked in position by advancing the locking bar, B, by means of the lever, C, until the front end of the bar projects into a recess provided for the purpose in the socket of the box. The charging bar, A,

PLATE X*a*.—Broadbent Overhead Charging Machine with Slewing Motion.

[*To face page 162.*

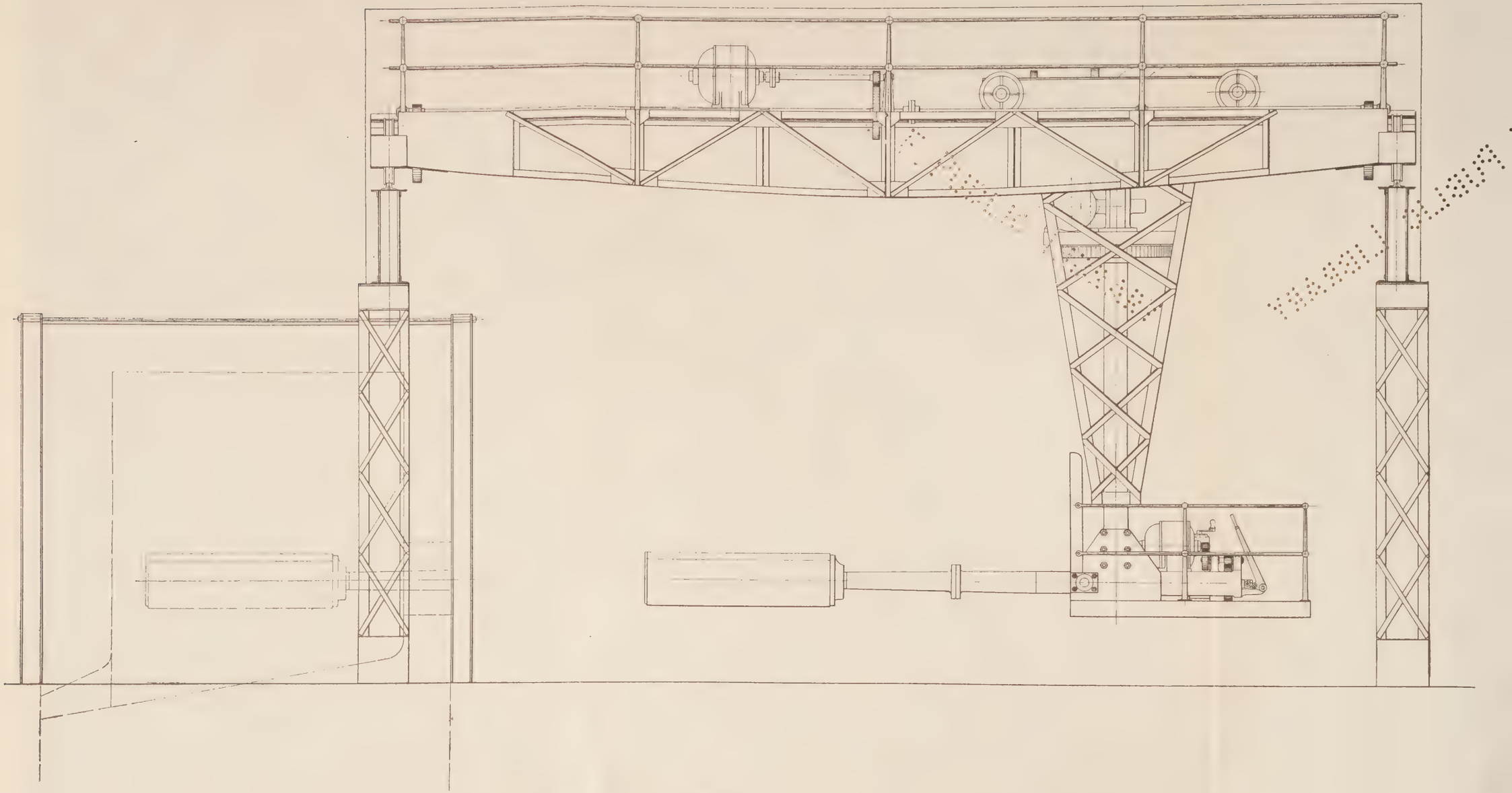


Fig. 150.

is hollow, to allow the locking bar to move within it. The machine is actuated by motors, for moving the machine longitudinally, raising and advancing, or withdrawing the bar, or for twisting the bar to empty the boxes. This machine is regarded as very satisfactory by practical men, and effects great saving in labour and time in charging.

Figs. 148 and 149 illustrate the latest types of low ground and overhead charging machines. They are arranged to pick up the boxes from the bogies at the back of, or any other position on, the charging platform, and slew round to charge into the furnace. This arrangement has considerable advantages over the non-slewing machine shown in fig. 147, which can only pick up the boxes from a bogie in front of the charging platform.

Broadbent Overhead Charging Machine.—This is an overhead electrical charging machine, similar in general design to the Wellman-Seaver machine, made by Thomas Broadbent & Sons, Limited, of Huddersfield. The canting motion, cross traversing, longitudinal travelling motion, and slewing are operated by separate motors running at speeds from 500 to 520 revolutions per minute. The machine can be slewed round at the rate of 2 revolutions per minute. The general design is shown in fig. 150.

Working the Charge for Dead Soft Steel.—When once the furnace is charged, the "melter" has nothing to do but watch his furnace and reverse his valves every twenty minutes until the charge is melted, which usually takes about three hours. When the bath is clear—*i.e.*, quite melted—lumps of pure hematite in small quantities at a time are thrown into it, and care must be taken not to add too much ore at first, or the charge will boil violently and flow out at the furnace doors; but, if added cautiously, the charge will begin to "boil" quietly. The boiling is caused by the evolution of CO, due to the Oxide of Iron reacting upon the Carbon in the molten metal, thus—

$$(1)\quad C + Fe_2O_3 = CO + 2FeO$$
$$(2)\quad 2C + 2FeO = 2CO + 2Fe$$
$$\text{or } (3)\quad 3C + Fe_2O_3 = 3CO + 2Fe$$

These reactions continue until nearly the whole of the Carbon has been removed, and the "melter" takes samples from time to time with a small ladle known as a spoon, hammers them flat, quenches them in water, breaks them in two, and, from the fracture, judges how the process is proceeding. With practice it is surprising how accurately these men are able to judge the percentage of Carbon present from the fracture, and to decide when the metal is ready for tapping. If the Carbon has not been sufficiently reduced, and the bath is beginning to go off the boil, more ore is added; but if, as is sometimes the case, the Carbon is reduced beyond the point required, pig-iron must be added to bring the metal back to the required degree of carburisation.

For dead soft steel or boiler plate quality, the bath is worked down to about 0·12 per cent. of Carbon, and then the furnace is got ready for tapping. Before actually tapping it is usual to "pig back" by adding a few half pigs of pig-iron to the bath, to keep it well on the boil, but not sufficient to appreciably affect the percentage of Carbon, and then the Ferro-Manganese—a rich alloy of Manganese and iron, containing about 6 per cent. of Carbon—is either added in lumps in the furnace, or, more generally, is broken very small, about the size of peas, and allowed to fall in the stream of metal as it flows from the furnace into the ladle. The complete operation usually takes about 7½ hours to 8 from the time that the furnace is charged, and allowing

time for charging by hand and repairs, a charge will be tapped about every twelve hours from each furnace.

Tapping the Charge.—The tapping of the furnace is effected by driving with sledges a steel-pointed bar through the fireclay and sand of the tap-hole, and afterwards knocking the bar out by means of "dogs" fixed by wedges to its end. Directly the hole is free, the head melter, working from the charging side of the furnace, enlarges the hole by pushing a steel "pricker bar" (fig. 155) into it from the inside of the furnace, until he is satisfied that the hole is quite clear and the metal flowing freely.

During the teeming of the metal into the moulds, a small sample is caught in a hand-ladle, poured into a cast-iron mould, and taken to the smith's shop to be tested for welding and cold bending, as described under the acid Bessemer process (p. 57). The sample is afterwards used for analysis.

It is very important to have a fairly fluid slag, as, apart from retarding the oxidation of the metal during the working of the charge, a thick pasty slag is very troublesome when tapping.

If the slag has a tendency to be thick, the melter often thins it by throwing a lump or two of limestone into the furnace. On the other hand, it is equally important not to have a very thin slag, as this usually means a slag very rich in Oxide of Iron or Manganese, and liable to produce wild over-oxidised metal. At the end of the operation the slag should be what is known as clean—*i.e.*, as free as possible from oxide, and fairly thick, but, at the same time, fluid and not pasty. To be able to decide what is and what is not a good "tapping slag" requires considerable experience, and is one of those things which can be learnt only by practice; but it is a matter of great importance, and a practical point which should always receive most careful attention.

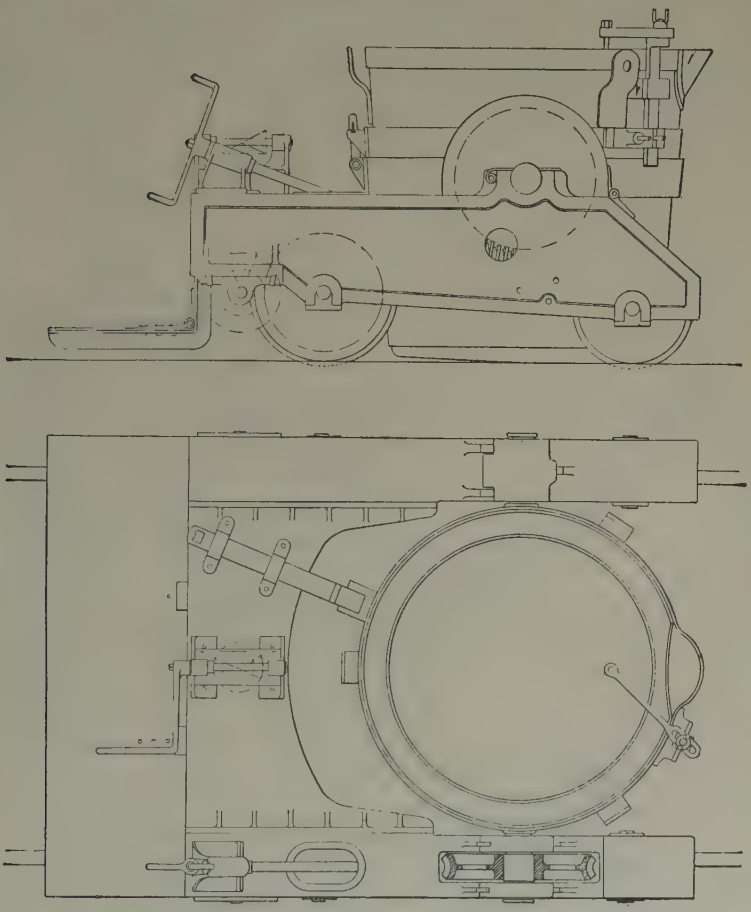
Precautions to be Observed.—A most important point in working a Siemens furnace is to always see that the tapping-hole is kept free from metal and slag, and a good furnaceman will take the greatest care to see that all metal is worked out of the hole before he proceeds to "make it up" again with anthracite and fireclay for another charge, which is usually done about fifteen minutes after tapping.

If the tapping hole is carefully attended to, "break outs" or "hard taps" will be very rare, although, despite the greatest care, they will occasionally occur.

In the event of a break out—*i.e.*, the tapping-hole giving way before the heat is finished—the ladle, if possible, is got under the tap-hole; but, if this cannot be managed, the metal must be allowed to run into the pit, and be broken up as soon as possible. In case of hard taps, little can be done except to sledge away until the bars penetrate the hole, and a set of well-pointed bars should always be at hand for such an emergency.

The Ladle.—The casting ladle, as regards arrangement of stopper and other details, is identical with that described on p. 25, fig. 31, used in Bessemer practice, but instead of being carried on a centre crane it is more usually mounted on a carriage with wheels which can be moved by hand gearing or drawn along by a locomotive, or by other means. The arrangement shown in figs. 151, 152, from drawings supplied by Messrs. Stevenson & Co., of Preston, is the one usually adopted in England, where the straight pit (Plate viii., fig. 125) is used, although in some works centre casting cranes similar to those employed for Bessemer works are employed. Where the system of casting on cars is being introduced into works, the ladle mounted on the carriage (as shown in the figure) is not suitable, as there is no means of raising the ladle up above the floor level, and

if used it necessitates running the ingot cars on rails in a pit sunk below the floor level. By far the best arrangement, and that now being generally introduced into modern works, is one in which the ladle is suspended from an overhead crane running in front of the furnaces. This enables the ladle to be very readily raised or lowered, to be moved along to any furnace, and the casting to be done any reasonable distance in front of



Figs. 151, 152.—Casting Ladle for Siemens Furnace for use with straight pit.

During teeming the carriage can be moved from mould to mould either by tooth gearing worked by hand, or it can be drawn along by chain or rod attached to a locomotive, and when it is required to move it any distance, as from one end of the shop to the other, the latter is always used. It is turned over by the worm which gears into the worm wheel keyed on to the trunnion, as shown in the sketch.

the furnaces, according to the span of the crane. In fig. 153, Plate xi., is shown a modern electric overhead crane, with all the latest improvements to ensure rapidity in working and easy control, combined with safety to the workmen. The details will be readily understood from the sketch and description.

Cranes for Ingot Stripping.—The difficulty in "stripping" the ingots and clearing the pit of a Siemens furnace plant is not nearly so great as in the case of the Bessemer plant, as heats from each Siemens furnace are ready for teeming only once in every 10 hours instead of 40 to 50 minutes. In a large Siemens plant different furnaces may be ready to tap at frequent intervals, but the pit space in front of any particular furnace will be required only once every 10 hours, so that there is this time to remove the ingots and reset the pit with other moulds. In ordinary work the pit is usually cleared as rapidly as possible, so that the ingots may be taken while hot to the re-heating furnaces; but apart from this there is no great hurry, and one good locomotive crane, by going from furnace to furnace, can do all the pit work for several furnaces.

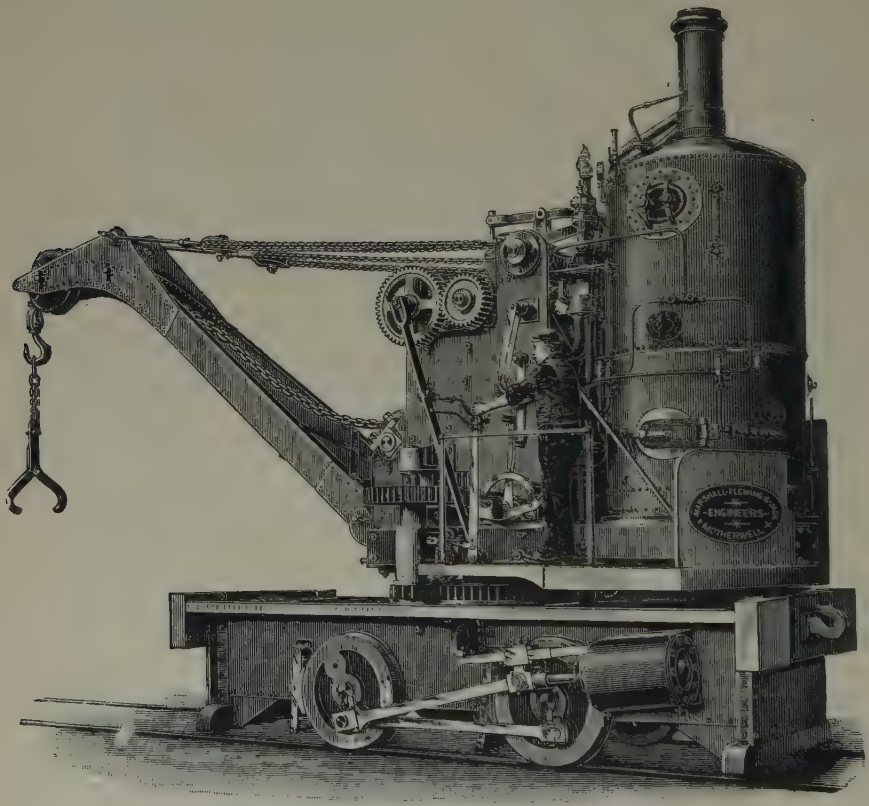


Fig. 154.—Travelling Crane for Steel Works.

Fig. 154 shows the type of crane commonly employed in an open hearth plant for handling the ladle carriage and lifting the ingots and moulds, the one in question being made by Messrs. Marshall, Fleming & Jack, of Motherwell. The travelling wheels are driven by engines separate from those used for lifting and slewing the load, thus giving a considerable increase in speed and convenience in working. The crane will lift 8 tons at 15 feet radius, or 12 tons at 10 feet, and can be used for shunting trucks or bringing in materials from the sidings for use in the mills or melting shop.

PLATE XI.—Electric Overhead Ladle Crane.

The main bottom block consists of a heavy steel forging, A, having its two ends turned to form gudgeons, on each of which is pivotted a compensating beam, B, with arms of equal length. The extremities of these beams receive the nests of sheaves, C C, which form the lower ends of the four sets of lifting tackle. The steel forging, A, serves as a distance piece to maintain the tackles in their relative vertical positions, and also as a suspension bar for the two long forged-steel hooks, D D, in which the trunnion of the ladle rest, and which are clamped to the suspension bar. Besides these, a short double hook, revolving on ball bearings, is attached to the bar at its centre for lifting weights other than ladles. This latter is not shown in the sketch.

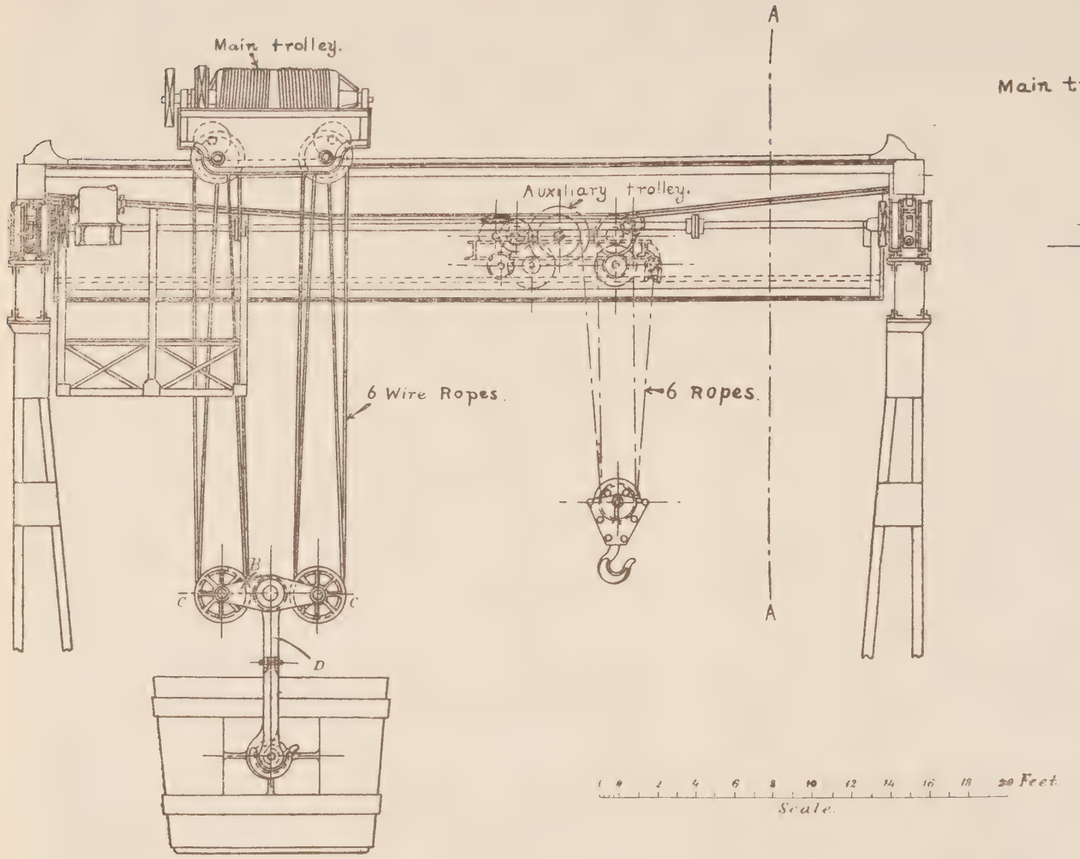


Fig. 153.

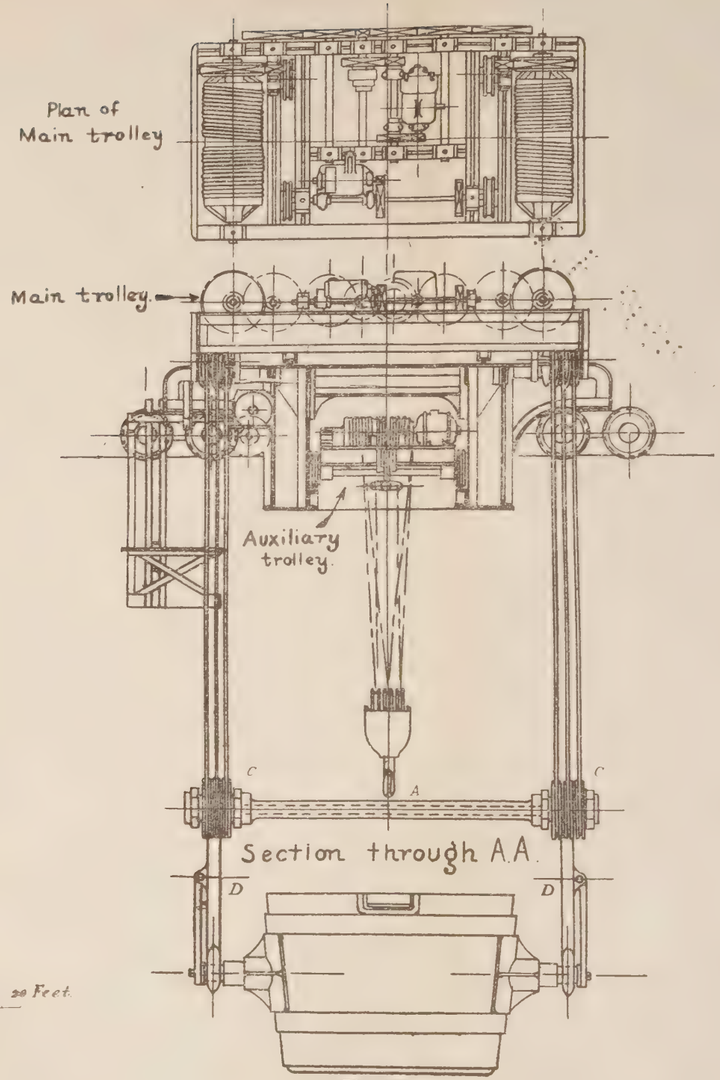


Fig. 153a.

Repairing the Bottom.—After the charge has been tapped from the furnace the tapping hole is "made up," as described, with fireclay and anthracite; the bottom of the furnace should be carefully examined for any holes, and if these exist, or the banks are cut away, they must be carefully repaired by spreading silica sand over the bad places, and glazing

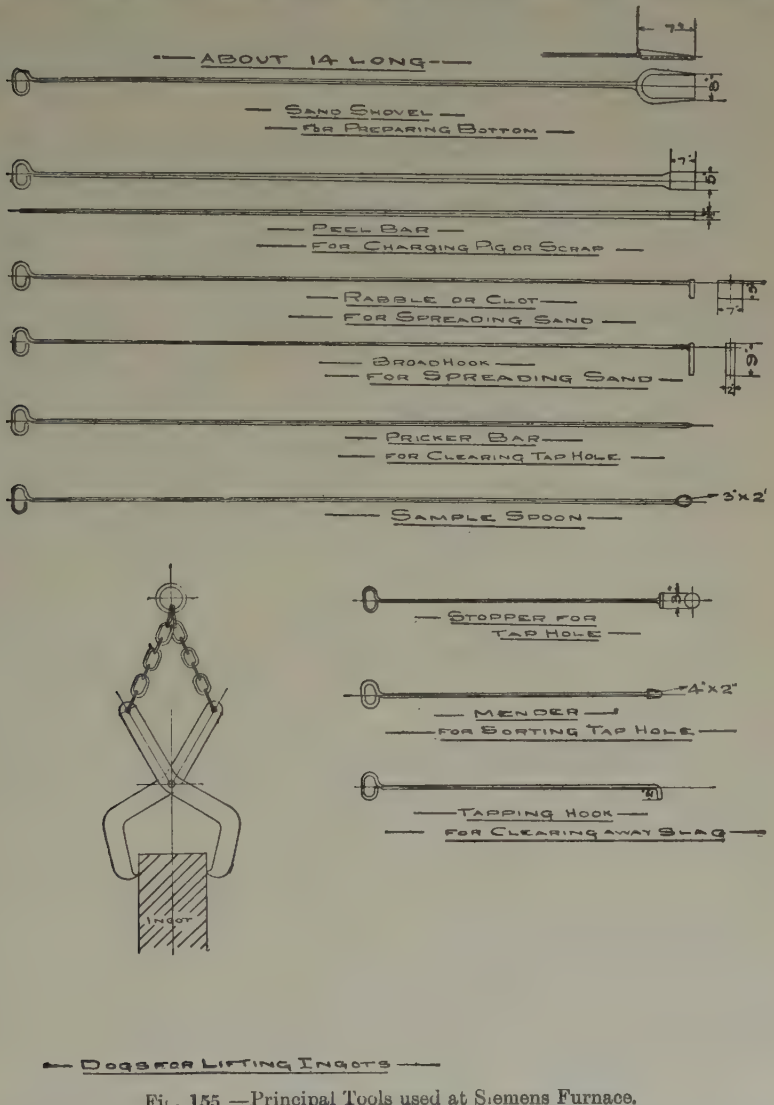


Fig. 155.—Principal Tools used at Siemens Furnace.

it on, after which the furnace is ready for another charge. It is important to lose as little time as possible between the charges, not only on account of the actual saving in time, but also to avoid the cooling down of the furnace. In fig. 155 are given sketches of the principal tools used in repairing and working a Siemens furnace.

In America, according to Campbell,* the scrap, instead of being charged cold with the pig-iron, is occasionally heated in a separate furnace while the pig is melting, and is then charged hot into the molten bath of metal, but so far as the author is aware this practice is not followed anywhere in this country, and is exceptional in America; and it is more than doubtful if it presents any advantages. In cases where very light scrap has to be used, as it is often impossible to charge the whole of the scrap before melting, it is best then to bundle it and charge from time to time into the molten bath, but with heavy scrap it is nearly always possible to charge it with the pig.

Reactions in the Acid Siemens Process.—In the acid process neither the Sulphur nor Phosphorus is to the least extent eliminated, and both, therefore, increase relatively in the finished steel as compared with the percentages in the original charge, and hence the first essential in selecting pig and scrap for the process is that they should be low both in Sulphur and Phosphorus; in no case should either constituent exceed 0·050 per cent. for high-class steel. The percentage of Silicon allowable in the pig-iron will vary with the special conditions of working, such as the amount of scrap available, as it is only necessary to have just enough Silicon in the charge to form, together with the Silica derived from the ore, furnace bottom, &c., sufficient slag to cover the metal. It is obvious, therefore, that if 30 per cent. of scrap is to be charged, a higher Silicon pig can be used than when only 10 per cent. of scrap is charged; and if no scrap at all is available, a pig-iron very low in Silicon should be used.

The following may be taken as typical pig-irons, suitable for manufacture of high-class acid open hearth steel under English conditions of working:—

	1	2	3	4
Carbon, . . .	3·500	3·210	3·640	3·600
Silicon, . . .	1·890	2·350	2·520	2·100
Sulphur, . .	0·030	0·040	0·025	0·030
Phosphorus, . .	0·035	0·038	0·030	0·032
Manganese, . .	0·700	0·680	0·900	0·880

Both the Sulphur and Phosphorus will frequently, in Hematite pig-iron, run up to 0·050, or even 0·060, but in this case it should only be used to mix in small proportions with better grade iron, as otherwise the Phosphorus and the Sulphur will exceed 0·06 per cent. in the finished steel. It is often desirable to get pig-iron lower in Silicon than 1·8 per cent., but in this country it is very difficult to do so, without getting an iron too high in Sulphur. Small quantities of low Silicon and Sulphur pig-iron may occasionally be obtained, but not regular supplies, so that higher Silicon iron than is necessary has generally to be used to avoid the production of high Sulphur steel.† Low Sulphur and low Silicon iron might be obtained by using a high manganiferous pig-iron, but Manganese is very objectionable, as it rapidly cuts away the Silica lining of the furnace, and tends to make the slag too thin. Many engineers now decline to accept for structural purposes steel in which either Phosphorus or Sulphur exceeds ·06 per cent., and consequently it is very important to start with pure materials. In other cases, where an exceptionally high-class material is required, the Phosphorus and Sulphur have to be below 0·04 per cent., and in such cases it is impossible

* *Trans. Amer. Inst. Mining Engineers*, vol. xx., p. 399.

† Several West of England iron works have recently altered their blast furnaces to produce iron similar to that obtainable in America, and are now regularly supplying low Silicon and low Sulphur pig.

to fulfil the conditions without using a large proportion of Swedish pig-iron, or very best selected English Hematite, exceptionally low both in Sulphur and Phosphorus. It is, however, unusual to use Swedish pig-iron in this country for manufacture of *dead soft* steel, the high-class West of England Hematites being equal to all ordinary requirements. Swedish is, nevertheless, used to a considerable extent for higher Carbon steel when special purity is required, and in such cases the Silicon in the pig is frequently less than 1 per cent., showing that the process does not necessitate such high Silicon pig-iron as is usually employed in England. The difficulty of obtaining supplies of pig-iron low both in Silicon and Sulphur is the real reason why such silicious irons are used.

In working charges with 20 to 25 per cent. of scrap, pig-iron with 1·75 to 2·5 per cent. of Silicon is found to give very good results, although more silicious pig can be used without interfering with the quality of the product, but it is very wasteful, and requires great care in working.

One disadvantage of using a very silicious pig-iron is that a very silicious slag is formed, which is inclined to be infusible, and to interfere with the working of the furnace, and fluidity has to be obtained by additions of Oxide of Iron to combine with this Silica, with the result that a larger percentage of iron is lost in the slag.

On the other hand, it is important not to go to the other extreme, as if a large excess of scrap with low Silicon pig is used, the bath will be desiliconised, and practically decarburised when melted, will be thick and sluggish, will rapidly oxidise, and besides scarifying the furnace bottom, there will be a great tendency for the steel to be red short.

The following may be taken as a typical charge for soft steel :—

PLATE CHARGE SHOWING YIELD AND SLAG.

Original Charge—

	Tons.	Cwts.	Qrs.	Lbs.	
Pig-Iron,	16	5	0	0	
Scrap,	4	0	0	0	
80 per cent. Ferro,	0	3	0	22	added at end of heat in the ladle.
Total charge,	20	8	0	22	

Yield of ingots at cogging mill, 19 tons 1 cwt. 3 qrs. = 94·07 per cent.

	Metal and Scrap Used.		Finished Steel.	Slag Analyses.	
	Pig-Iron.	Scrap.			
Carbon,	3·58	0·18	0·180	Silica, SiO_2,	57·00
Silicon,	2·42	0·038	0·028	Ferrous Oxide, FeO,	25·12
Sulphur,	0·028	0·047	0·051	Alumina, Al_2O_3,	3·32
Phosphorus,	0·04	0·044	0·048	Oxide of Manganese, MnO,	7·62
Manganese,	1·22	0·51	0·48	Lime, CaO,	5·50
...	...	...	...	Magnesia, MgO,	1·08
...	...	...	...	Phosphoric Acid, P_2O_5,	·063
...	...	...	...	Sulphuric Acid, SO_3,	Trace.
...	...	...	...	Alkalies (not estimate),	...
					99·703

Weight of slags, 2 tons 16 cwts. 2 qrs.

The yield on this charge is rather low. It should not be less than 95 per cent. on an average, and in some cases a yield of 97 per cent. is obtained.

Elimination of Impurities.—The elimination of the impurities in the charge takes place in two stages—

(1) During melting, by the oxidising action of the flame.

(2) After melting, by the action of Oxides of Iron formed during the melting period or added to the melted charge.

The percentage of impurities oxidised during melting will vary considerably with the composition of the pig-iron, the relative proportions of scrap and pig-iron, and the mechanical condition of the scrap—whether light or heavy—and also, of course, with the working condition of the furnace. Taking a furnace in good working order, with a charge of 25 per cent. scrap, the percentage of Silicon oxidised during melting will usually vary from 33 to about 50 per cent., and the Carbon removed will be about 30 per cent.; the Manganese is almost entirely oxidised during the melting. The Silica and Manganese Oxide, with some of the Oxide of Iron formed, unite with the sand adhering to the pigs and some of the furnace bottom to form a fluid slag, which is essentially a double Silicate of Iron and Manganese.

The following analyses of samples from different charges worked at the Consett Steel Company, and kindly furnished by Mr J. P. Walton, illustrate the removal of Silicon and Carbon during melting, and other analyses in the possession of the author confirm these results, although in many cases the percentage of Carbon removed in a given time is higher.

TABLE XXVI.—Oxidation of Carbon and Silicon in the Open Hearth Process during the Melting of the Charge.

Number of Charge.	Charge consisted of				Composition of Pig-Iron.		Calculated Average Composition of Charge. Pig-Iron as per Analysis. Steel Scrap averaged C = ·20, Si = ·03.		Melted Charge before Addition of Ore.	
	Pig-Iron.		Steel Scrap.							
	Tons.	Cwts.	Tons.	Cwts.	C.	Si.	C.	Si.	C.	Si.
B 173, .	23	0	4	15	4·19	1·874	3·507	1·558	2·70	·750
C 400, .	23	0	4	15	4·24	1·563	3·549	1·300	2·75	1·070
A 274, .	23	9	4	15	4·20	1·740	3·660	1·390	2·78	1·134
B 171, .	23	6	4	15	4·20	1·740	3·620	1·380	2·91	·957
E 282, .	21	9	6	10	4·20	1·740	3·210	1·300	2·64	·630
F 258, .	23	0	4	15	4·20	1·740	3·569	1·400	2·86	·817

The following analyses of samples taken during the working of a boiler plate charge have kindly been supplied by Mr. Campion:—

	Original Charge, Average Composition.	Charge Melted.	1 hour later.	Boiling 20 mins.	Boiling 1 hour 20 mins.	Boiling 2 hours 20 mins.	Ready.	Finished Plates, Boiler Quality, for Flanging.
Total Carbon,	3·360	3·24	2·69	2·150	1·510	·570	·170	·170
Silicon, . .	1·990	1·33	·50	·046	·041	·028	·028	·032
Sulphur, . .	·031	...	...	...	...	..	...	·046
Phosphorus,	·044	...	...	...	...	...	...	·048
Manganese, . .	·630	...	...	...	...	...	...	·490

In America, where iron containing much less Silicon—frequently only 1 per cent.—and larger proportions of scrap are used, practically the

whole of the Silicon and a large percentage of Carbon are removed during melting, as is shown by the following Table, given by Campbell,* which embodies the average of nineteen consecutive heats under Group I., melted with producer gas, and the average of six heats under Group II., melted with oil vapour :—

TABLE XXVII.—Elimination of Impurities in an Open Hearth Charge.

Nature of Sample.		Group I.	Group II.
Pig-iron, pounds,		14,700	20,700
Steel scrap, pounds		45,550	36,800
Composition of original charge, per cent. (estimated),	Si	0·40	0·65
	Mn	0·90	0·85
	C	1·00	1·50
Metal when melted, per cent.,	Si	·02	·05
	Mn	·09	·06
	C	·54	·64
Slag after melting, per cent.,	SiO_2	50·24	49·46
	MnO	21·67	13·16
	FeO	23·91	33·27

In cases where very light readily oxidisable scrap is charged, a considerable amount of Oxide of Iron may be formed and react locally on a part of the charge, and practically decarburise it before the rest is melted, although such a slag, taken as a whole, may not contain sufficient Oxide to make it an active working slag.

The composition of the charge of the furnace should be regulated, as far as possible, when making mild steel, to ensure the removal of as much of the Silicon and Manganese as possible during melting, and leave about 2·0 to 2·5 per cent. of Carbon in the bath of metal, which will be sufficient to ensure a vigorous reaction between the ore additions and the metal, and complete the removal of the Silicon. Much more Carbon than this unduly prolongs the process without any apparent compensating advantage, and with much less than this the metal does not come vigorously on the boil, and is what is termed sluggish in the furnace, with the result that it will probably be over-oxidised before it is ready to tap. This applies only to English practice, where we may assume that, as a rule, about 0·8 per cent. of Silicon will remain in the metal after melting. In cases like those given by Campbell, where the whole of the Silicon is removed during melting, from ·5 to ·7 per cent. Carbon left in the molten metal will be sufficient to work the heat down with, although the higher limit is preferable, or even 1·0 per cent.

Composition of Slag.—The oxidation of the metal after melting depends upon the composition of the slag and the temperature of the furnace, and both these factors are of the greatest importance.

In a most exhaustive paper by Campbell,† which has already been referred to, and which forms the most complete contribution to the metallurgy of the Siemens process ever published, he traces the chemical history and variations in composition of the slag in a large number of charges working both with producer and with oil gas; and from the results, given

* Campbell, *Structural Steel*, p. 124.

† *Trans. Amer. Inst. Mining Engineers*, vol. xxii., 1893.

in the following table, it will be seen that the variation in Silica and Oxides of Iron in the slag, directly *after melting*, and just before tapping, is comparatively little. In the case of A, the figures are the average of nineteen heats, and in B, average of six heats :—

TABLE XXVIII.—Variations in Composition of Slags.

	Silica.		Oxide of Manganese, MnO.		Oxide of Iron, FeO.		Oxide of Iron and Manganese, FeO and MnO.	
	After Melting.	Before Tapping.	After Melting.	Before Tapping.	After Melting.	Before Tapping.	After Melting.	Before Tapping.
A. 19 heats producer gas,	50·24	49·40	21·67	16·50	23·91	29·79	45·58	46·29
B. 6 heats oil gas, . .	49·46	49·36	13·16	11·30	33·27	34·11	46·43	45·41

The above results show that the Silica was practically the same in the slag just after melting as immediately before tapping, that the Oxide of Mn gradually decreased, that the FeO varied somewhat, but that the sum of the two Oxides, MnO and FeO, was practically constant.

For a good working slag what is required is sufficient Oxides of Iron and Manganese, to completely combine with the Silica present, so that any ore added is free to oxidise the remaining impurities in the metallic bath. When additions of ore are made from time to time to a slag in this condition, the percentage of iron in the slag is hardly affected at all, all the Oxide of Iron added being almost immediately reduced by the impurities in the metal, the iron passing into the bath.

Table xxix., taken from Campbell's paper, gives the analyses of the slag after various additions of ore have been made, and it is surprising how little the composition of this slag is altered. It is true that the amount of FeO is increased by nearly 2·5 per cent. after the addition of 1,500 lbs. of ore. But as Campbell points out, the stable condition of the slag is not determined by the percentage of FeO alone, but by the sum of the Oxides, FeO and MnO, and provided they are present in sufficient quantity to satisfy the Silica, a state of equilibrium is established, and no more Oxide passes into the slag, but it is free to act upon the bath of metal. From time to time some Silica is taken up from the hearth of the furnace, and small quantities of Oxide will be required to combine with this, and also any silicious matter introduced with the ore; but with these exceptions the Iron Oxide *added* should be practically reduced, unless a large excess of ore is added towards the end of the operation.

TABLE XXIX.—Showing how Composition of Slag is Affected by Additions of Different Quantities of Ore.

	Before Addition of Ore.	After 500 lbs. of Ore Added.	After 1,000 lbs. of Ore Added.	After 1,500 lbs. of Ore Added.
Silica, per cent., ...	51·90	51·98	52·77	52·75
Oxide of Manganese, MnO, per cent., .	18·50	17·51	16·29	14·93
Oxide of Iron, FeO, per cent., . . .	26·04	26·53	26·92	28·45
FeO and MnO, per cent., . . .	44·54	44·04	43·21	43·38

In a paper* read before the Iron and Steel Institute by Messrs. A. McWilliam and W. H. Hatfield on the elimination of Silicon in the open hearth furnaces, the authors give the results of two experimental heats in which the composition of the slag in relation to Silica and Oxides of Iron was varied during the working of the charge, so that the effect of such variation on the removal of impurities might be seen. In Tables xxx. and xxxi. are given analyses of the metal and slag from samples taken at frequent intervals.

TABLE XXX.—Details of Special Charge No. 1.

Time.		Composition of Bath.			Additions.		Consistency of Slag.	Composition of Slag.		
		C.C.	Si.	Mn.	Materials.	Cwt.		FeO.	Fe_2O_3.	SiO_2.
Hr.	Min.	Per cent.	Per cent.	Per cent.				Per cent.	Per cent.	Per cent.
11	10	1·60	0·78	0·48	(Melted)	...	Thin	...	...	...
11	12	...	...	...	Ore	10	...	...	...	...
11	30	...	...	...	,,	4	...	...	...	...
11	45	1·54	0·35	0·20	(Boil)	...	Thin	30·8	7·1	45·0
12	15	1·55	0·047	0·11	...	..	,,	...	...	...
12	20	...	...	...	Ore	2	...	...	...	...
12	45	1·22	0·045	0·09	...	...	Thin	...	...	...
12	50	...	...	...	Ore	3	...	...	...	...
1	0	...	...	...	,,	1½	...	...	...	...
1	15	0·94	0·028	0·042	...	...	Very thin	24·1	2·5	52·8
1	16	...	...	...	Ore Lime	1 ¾	... ...	...	...	...
1	30	0·86	0·02	0·04	...	...	Thin	...	...	...
2	0	0·73	0·022	...	...	...	Becoming thicker	...	...	...
2	30	0·65	0·034	0·056	...	...	Fairly thick	...	...	...
3	0	0·55	0·061	0·068	...	...	Thick	...	...	...
3	30	0·40	0·078	0·08	...	...	,,	...	...	...
3	50	0·38	0·088	0·095	...	...	Thickest	20·8	1·1	56·8
3	55	...	...	...	Ore	1	...	...	...	...
4	5	...	...	...	,, Lime	¾ ½	... ...	...	...	...
4	25	0·26	0·031	0·072	...	...	Becoming thinner	...	...	...
4	30	...	...	...	Ore	1	...	...	...	...
4	35	...	...	...	Lime	⅛	...	...	...	...
4	45	...	...	...	Ore	½	...	...	...	...
4	50	0·16	0·024	0·065	...	...	Fairly thin	...	...	...
4	55	...	...	...	Ore	¼	...	...	...	...
5	13	0·14	0·025	0·065	...	..	Fairly thin	21·9	0·57	53·4

Finished steel—**Combined Carbon**, 0·31; **Si**, 0·045; **Mn**, 0·58.

It will be seen that with a thin slag—that is to say, a slag relatively low in Silica—the oxidation of Silicon and Manganese was comparatively rapid, but with a thick or silicious slag not only were Silicon and Manganese not removed, but they were actually reduced from the slag and passed back into the metal. The authors maintain that the results are due to the variations in composition of the slag and not to its fluidity, as when it was thinned by other means than the addition of oxidising agents the impurities were not removed to the same extent.

* *Iron and Steel Inst. Journ.*, 1902, vol. *i.*, p. 58.

These results entirely support Mr. Campbell's conclusions that the activity of the slag as an oxidising agent depends upon the relation of the percentage of Silica to the Oxides present, and that it is the Oxide in *excess* of that required to satisfy the Silica in the slag which must be relied upon to do the work of oxidation. It is probable that the temperature has some influence on the removal of the Silicon, although this does not appear to be very great, at all events within the variations of temperature common in everyday practice.

TABLE XXXI.—Details of Special Charge No. 2.

Time.		Composition of Bath.			Additions.		Consistency of Slag.	Composition of Slag.		
		C.C.	Si.	Mn.	Materials.	Cwt.		FeO.	Fe_2O_3.	SiO_2.
Hr.	Min.	Per cent.	Per cent.	Per cent.				Per cent.	Per cent.	Per cent.
9	45	1·60	0·80	0·64	(Melted) Ore	6	...	...	...	...
10	25	1·58	0·28	0·27	,, (Boil)	4	Thin	22·1	2·5	48·6
10	52	1·47	0·026	0·064	...	...	Fairly thin	...	...	...
10	55	...	...	...	Ore	2	...	...	...	...
11	15	...	...	...	,,	2	...	...	...	...
11	25	1·08	0·017	0·054	...	...	Thin	...	...	...
11	30	...	...	...	Ore	3	...	...	...	...
11	50	...	...	...	,,	2	...	...	...	...
11	55	0·82	0·016	0·051	...	...	Thin	...	...	...
12	15	...	...	...	Ore	1	...	...	...	...
12	20	0·64	0·017	0·053	...	...	Thinnest	20·5	2·1	53·0
12	55	0·47	0·035	0·059	...	...	Becoming thicker	...	...	...
1	25	0·39	0·066	0·065	...	...	Fairly thick	...	...	...
2	0	0·33	0·058	0·071	...	...	Thickest	18·1	0·6	54·6
2	5	...	...	...	Ore	1¼	...	...	...	...
2	30	0·24	0·032	0·056	,,	1	Becoming thinner	...	...	...
2	45	...	...	...	,,	½	...	...	...	...
3	0	0·19	0·032	0·055	...	...	Fairly thin	23·0	0·3	51·6

With careful work there is little risk of getting too high a temperature, although this is possible with a silicious iron, a rich gas, and a quick draught. We then get the same result as in the Bessemer converter—that the Carbon is oxidised preferentially to the Silicon, and we obtain a decarburised metal high in Silicon. The possibility of this is of course increased when working a very silicious iron, and hence it is important to regulate the temperature of the furnace according to the composition of the charge, and to obtain pig-iron as regular as possible, so that the furnacemen may not have to vary the conditions of working more than is absolutely necessary. The essential condition is to have sufficient heat to maintain a fluid bath of metal and slag, and to enable the metal to be tapped at such a temperature that it can be cast into the ingot moulds without "skulling" in the ladle.

Sulphur in Producer Gas.—In open hearth steel manufacture the Sulphur in the finished metal is often found to be higher than would be expected from the composition of pig and scrap used.

This may be due to Sulphur either absorbed from the gases, or introduced in the ore, and consequently care must be taken to see that good coal, low in Sulphur, is used in the gas producers, and non-

sulphurous ore in the furnace. It is the practice in some works to mix a little lime with the coal slack before it is used in the producers, and, provided it can be done without causing trouble with clinkering, it undoubtedly has a tendency to fix the Sulphur with the ash instead of allowing it to pass into the gases. The difficulty, however, is to add a sufficient quantity of lime to effect this without interfering with the regular working of the producer. In the opinion of many practical men, when, for any reason, the furnace is working sluggishly, and when the gas is said to be "cold," there is a much greater tendency for the bath to take up Sulphur than when working quickly, but the author is unable to offer any opinion as to whether this is due simply to a larger amount of gas being passed into the furnace to produce the required amount of heat, or to some other cause.

So far we have considered only the manufacture of dead soft or mild steel in the Siemens furnace, but as large quantities of steel are required of all degrees of carburisation, from ·200 to 1·000 and even higher, it is necessary to discuss the manufacture of these different classes of steel.

Axle, Tire, and Spring Steel, &c.—The principal purposes for which high Carbon open hearth steel is used are for the manufacture of axles, tires, springs, guns, wire drawing, armour plates, steel castings, and to a small extent for tool steels.

Steel for axles varies in Carbon content from 0·25 to 0·35 per cent., and has a stress varying from 30 to 40 tons per square inch. Tire steel varies in Carbon content from 0·30 to 0·70 per cent., and has a stress varying from 35 to 58 tons per square inch. Spring steel, for railway purposes, varies from 0·50 to 1·2 per cent. Carbon, according to the particular purpose for which it is required. The majority of steel castings contain from ·20 to ·40 per cent. Carbon, although for special purposes they are made as high as 1·0 per cent. Carbon.

Broadly speaking, there are three important methods of making high Carbon steel in the Siemens furnace, viz. :—

1. To work the charge of pig-iron, or pig-iron and scrap, in the usual manner, but to tap out the metal as soon as it has reached the desired point of decarburisation.

2. To work the charge down dead soft, or nearly so, as for mild steel, and then recarburise in the furnace by the addition of pig-iron or spiegel, or by a mixture of both.

3. To work the charge dead soft, and recarburise outside the furnace by the Darby* or other method of recarburisation.

In making axle steel, the practice more generally adopted is to tap out when the required degree of decarburisation has been reached, although for making the highest quality of material, many of the best makers prefer to work down and recarburise in the furnace. In the case of higher Carbon steel, such as tire steel, spring steel, and wire billets, with 0·50 per cent. of Carbon and over, it is usual to work down to about 0·20 to 0·30 per cent. of Carbon, and then bring back by charging pig-iron in the furnace.

In carrying out the manufacture by the second method, the charge of pig-iron and scrap is carefully worked down, so that when the bath contains about 0·3 per cent. Carbon the slag is thick and clean—*i.e.*, practically exhausted, or free from *active oxide*. Samples of metal are then taken, and are generally tested for Carbon by colour, which only takes a few minutes. The metal samples should be solid, and free from blowholes or honeycomb structure, and if either the slag or the metal is not right, pig-iron must be added, a few pigs at a time, until both are satisfactory. Too much emphasis cannot be laid upon the importance of getting both slag and metal in the

* See chap. viii., Basic Siemens, p. 189.

right condition before adding the metal for recarburising, as if any appreciable amount of Oxide of Iron remains in the slag the pig-iron added will react vigorously with the slag, considerable decarburisation will result, and the Carbon in the finished steel will be far lower than required. When the melter is satisfied both with his metal and his slag, he charges the pig required to give the necessary Carbon on the banks of the furnace, and allows it to melt down into the bath. It is then well rabbled or "rubbed up," the necessary additions of Silico-spiegel and Ferro-Manganese made, and the metal tapped. The Ferro-Manganese may be added either in the furnace immediately before tapping, or to the metal as it runs into the ladle. If steel with more than about 0·6 per cent. Mn is required, it is found that this becomes more evenly distributed if the Ferro is added in the furnace, in which case it is added in rather large lumps to guard against excessive oxidation. If added in the ladle, it should be in small pieces, not larger than hazel nuts.

The amount of pig-iron added for recarburising is calculated, so that when it has quite melted, the Carbon content of the bath shall be rather above that which is required, and it is then carefully worked down to the desired point. During the melting of the pig on the furnace banks, a certain amount of oxidation is of course taking place, and an allowance must, therefore, be made for this.

The amount of Carbon oxidised during the melting will vary with the percentage of Silicon in the pig-iron, the higher the Silicon the less the Carbon is oxidised, so that when using a Swedish pig with 1 per cent. of Silicon for recarburising (for steels where low Silicon is required) rather more must be added than when hematite pig containing 2·5 per cent. Silicon is used. In making ·50 per cent. Carbon steel, it is usual to work the bath down to 0·20 per cent., and a charge of about 7 tons 2 cwts. of pig and scrap would require about 14 cwts. of Swedish pig, with 4·0 per cent. Carbon and 1·0 per cent. Silicon, charged on the banks, to give ·49 to ·51 per cent. Carbon in the ingot, provided the slag was right before the Swedish pig-iron was charged into the furnace. Theoretically this should give ·54 per cent. Carbon, thus showing a loss of about ·03 to ·05 per cent. For ·60 Carbon steel, working under the same conditions, about ·3 cwt. more of pig-iron would be required. If grey hematite instead of Swedish pig is used to obtain the same result, rather less pig would be required. For ·70 Carbon steel, the bath may be safely worked down to ·30 before charging the recarburising pig-iron. A certain amount of Carbon will always be added by the Ferro-Manganese additions, and also by the Silico-spiegel, or Ferro-Silicon, when these are used, and allowance must be made for this.

Although it is the practice at some works to make tire steel from ·50 to ·70 per cent. Carbon by working down to the required point and tapping at once, this method of working for such high Carbon steels is not regarded as satisfactory by many steel makers.

It is extremely difficult to get a thick, quiet, inactive slag, with Carbon in the steel, at or above ·50 per cent., and unless the slag is practically exhausted as regards free Oxide at the time of tapping, it will be impossible to insure steel of the required Carbon content.

In cases of high Carbon steel, where low Silicon is required, excellent results may be obtained by running finely-ground anthracite on to the stream of metal as it flows into the ladle; this should be all in when the ladle is about three-quarters full of metal, and then sufficient Aluminium should be added to give a good solid ingot. If no Aluminium is added, or too little, the ingots are liable to be honeycombed, and if too much is added, although the ingots will be solid, they will "pipe" badly. If anthracite were pure Carbon, and there

were no loss, 2·24 lbs. would give ·100 Carbon when added to 1 ton of steel, but in actual practice about 3·12 lbs. are required, so that to raise the Carbon ·01 in a 10-ton charge, 3·12 lbs. are necessary.

In the case of tire steel, when great hardness to resist wear on the tread is required, combined with soundness and absence of all brittleness, a certain amount of Silicon in the steel is beneficial, and this is added to the bath just before tapping in the form of Ferro-Silicon or Silico-spiegel. About $\frac{1}{3}$ or $\frac{1}{4}$ of the Silicon present in the Ferro-Silicon is oxidised, so that to obtain ·15 to ·18 in the steel, sufficient Silicon pig or Silico-spiegel must be added to give ·22 per cent. of Silicon.

In all cases, whether hard or soft steel is being made, the casting temperature has an important influence on the quality of the steel produced, and is a question which has not received so much attention as it deserves. The point to aim at is to have *just sufficient* heat to teem the metal clear from the ladle, so that when the metal is once cast into the moulds it will set as rapidly as possible. The lower the casting temperature, in all probability the better the steel.

The following may be taken as a fairly typical charge for the manufacture of tire steels :—

	Tons.	Cwts.
Best selected pig-iron,	5	13
Scrap (selected),	5	0
Best grey pig-iron on banks after bath worked down,	1	0

Ferro (80 per cent.), 226 lbs; Aluminium, 8·5 lbs., added in ladle.
Silico-spiegel, 45 lbs., added to furnace just before tapping.
Analysis of finished steel—Carbons, ·54; Silicon, 0·224; Manganese, 0·65.

When it is intended to catch the Carbon on the way down, and tap without "pigging back," a much greater proportion of pig-iron is used, so as to give a higher initial Carbon content in the bath, and, consequently, a longer period of boiling; not more than 25 per cent. scrap should be used if steel with 0·60 per cent. Carbon is required. With such a proportion of scrap very excellent results can be obtained, and some makers prefer this method to recarburising in the furnace.

The following is a typical charge :—

	Tons.	Cwts.
Best selected pig-iron,	9	10
Scrap,	2	10

80 per cent. Ferro equal to 1 per cent. of charge; 70 ozs. Aluminium, added in the ladle.

This charge gave steel containing Carbon, 0·63 per cent.; Silicon, ·170 per cent.; Manganese, 0·60 per cent.

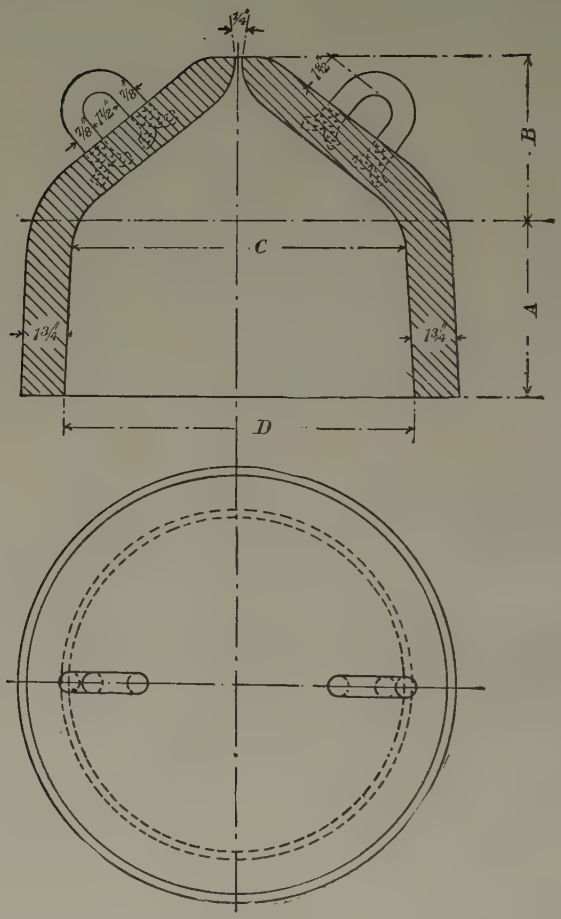
In the manufacture of tires, the metal, instead of being cast in a mould of the usual shape, is cast in special circular moulds known as cheese moulds, shown in fig. 156.

These are always cast in groups from the bottom, about four moulds being set on one bottom plate. In figs. 156 and 157 are shown plan of moulds and of bottom plate, with section of latter and git.

These ingots are flattened under the hammer, the centre punched out, and then finished in a special tire mill.

Washed metal* is now being largely used to replace Swedish pig-iron in the manufacture of high-class steels for making axles, and sometimes as much as 70 to 90 per cent. is charged with pig or with part pig-iron and part scrap, although usually it does not exceed 30 per cent.

* See chap. viii., Basic Siemens, pp. 195-196.



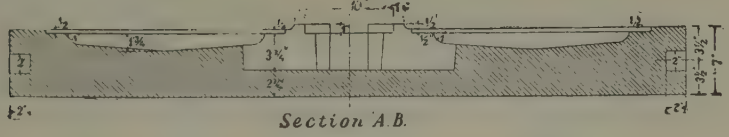
A	B	C	D
5 1/16"	6 1/2"	13 3/8"	14"
5¾"	6 1/2"	11¾"	12"
6 1/16"	6 1/2"	13 3/8"	14"
9 1/2"	6¾"	19 7/8"	20"

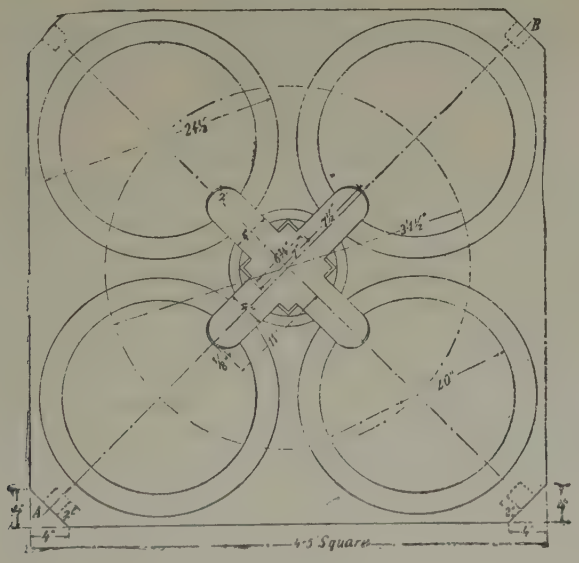
Fig. 156.—Cheese Ingot Moulds for Casting Ingots for Tires.

The following charges are from actual works' practice :—

	1.	2.	3.	4.
	Per cent.	Per cent.	Per cent.	Per cent.
Best selected pig, . .	6	5	15	6
Washed metal, . . .	20	5	5	20
Best axle or tyre scrap, .	74	90	80	70

When using such a large proportion of scrap as above, a portion of the pig-iron or washed metal would be reserved for charging on the banks to recarburise, as it would be difficult under these conditions to catch the bath at the right point.





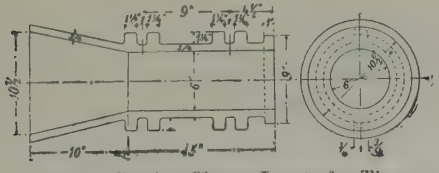


Fig. 157.—Bottom Plate for Casting Cheese Ingots for Tires. A group of 4 ingots is cast from one centre git.

Some engineers specify that a certain percentage of Swedish iron shall be used in the charge, and as the Sulphur and Phosphorus have generally

to be under 0·04 per cent., it is absolutely necessary to use either Swedish iron, washed metal, or one or two very special brands of English iron.

Many steel makers prefer, in the case of *axle steels*, which usually contain from ·25 to ·35 per cent. of Carbon, to catch the metal when the required point of decarburisation has been reached, rather than work down to nearly soft steel and then recarburise by charging pig-iron on the banks. When making steel *below 0·4* Carbon, most excellent results can be obtained by this method of working, and the difficulties of getting slag and metal into the right condition are considerably less than in case of higher Carbon steel; but even for these lower Carbon steels it is necessary to use a larger percentage of pig-iron to ensure a fairly long boil than if it is intended to recarburise in the furnace, and not more than 50 per cent. of scrap should be used in the charge.

In the manufacture of special steels or alloys for armour plates and other purposes, the charge is worked in the same way as for ordinary high Carbon charge, and then the special alloy of Ferro-Chrome, Nickel, &c., added, special care being taken to see that the slag is as free as possible from oxides. The ingots of these steels are usually cast from the bottom, to ensure greater soundness and a better surface or skin on the ingot.

CHAPTER VIII.

BASIC SIEMENS PROCESS.

The basic Siemens process, like the basic Bessemer process, depends, for the removal of Phosphorus, entirely on the formation of stable Phosphates, and this is effected by lining the furnace with a basic or neutral material, and by lime additions during the working of the charge. The furnace employed, with the exception of some minor details, is identical with that used in the acid process, and the method of working is the same, the impurities being oxidised partly by the air during the melting, and partly by the addition of solid Oxides of Iron to the molten bath after the charge is melted.

Early Practice.—In the early days of the basic Siemens process several furnaces were specially designed to meet the particular difficulties encountered, to facilitate repairs, &c., and to reduce the cost of construction; but after many trials it has been found that a furnace constructed on modern lines similar to that used for acid work gives the best all-round results in actual practice.

The Batho Furnace.—Amongst the earliest forms of modified furnaces used for basic work was the Batho furnace, which was greatly improved in various ways by Messrs. Riley, Dick, Wailes, and Hilton. In its earlier form it was a round furnace, and the roof was built in an iron frame, forming a lid, and was suspended independently of the walls of the furnace from girders above, arrangements being made for raising the roof bodily when the furnace required re-lining or repairs. A sketch showing the general arrangement of a modified form of the furnace of this type is given in figs. 158 and 159. The chief points urged in favour of these furnaces were, that the regenerators, being on each side of the body of the furnace, were quite independent of the latter and contained in separate iron casings so that in the event of a breakout there was no risk of the metal

getting into the regenerators; that it was impossible for a leakage of gas to take place between the gas and air regenerators, leading to the destruction of the brickwork; and that, the regenerators not being underneath the staging, the latter was much cooler for the men to work on. One modification of the furnace was to make the body elliptical (as shown in the sketch) instead of cylindrical, but with all these furnaces the difficulty of getting the gas and air ports to withstand contraction and expansion was so great that it has been found better to return to the rectangular furnace, with a solid square block for the ports, which is capable of resisting the great strain put upon it by contraction and expansion. The modern type of furnace (as shown in

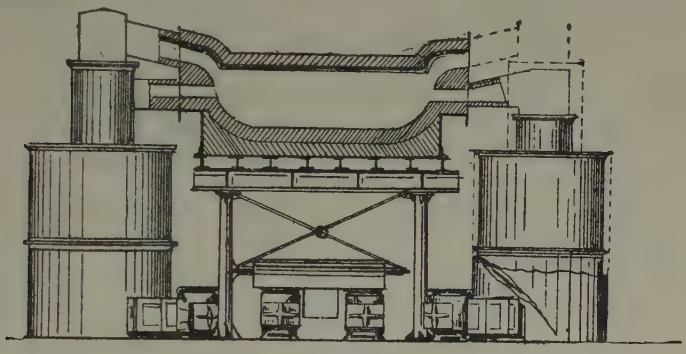


Fig. 158.

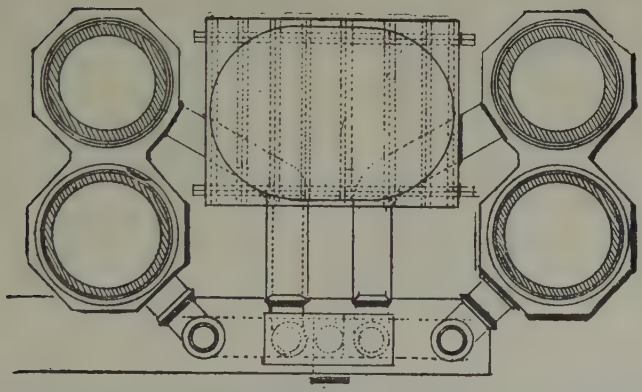


Fig. 159.—Sketches illustrating general arrangement of a Batho Furnace. Sectional plan and elevation.

figs. 127-130) practically has all the advantages claimed for the Batho furnace. The body of the furnace is independent of the regenerator arches; the regenerators are away from the bottom of the furnace, and there is practically no risk of air and gas burning, due to leakage of gas and air between the regenerators. It may be, therefore, taken as established by experience that the best form of furnace for basic Siemens work is that of the ordinary Siemens type, as far as general design is concerned, and it will differ only in the internal lining of the hearth or crucible, and the method of supporting the roof and other details. Owing to the very friable nature of basic material, it is not possible to build the entire working body of this; it would,

for instance, be quite impossible to build the roof with basic bricks, or even the entire walls, as they would not support the weight of the roof, and consequently part of the structure has to be of basic and part of acid materials. There is thus the danger of these two dissimilar bodies fluxing when in contact at high temperatures. It was to overcome these difficulties that the suspended roof of the Batho-Wailes furnace was designed, but it has been found that these difficulties of the fluxing of the two materials are not so serious in practice as theoretical consideration might lead us to suppose, and they have been successfully dealt with by practical men. It was discovered, when the basic Siemens process began to be adopted, that silica bricks of best quality might be in contact with basic material without any serious fluxing action, *provided they were not subjected to pressure.* This fact was soon taken advantage of, additional security being given by generally introducing a joint of some neutral infusible material like Chrome iron ore to form a neutral joint between the two bodies.

Lining the Furnace.—Probably the most simple way of lining a basic Siemens furnace is to build up the entire casing, from the bottom, with acid bricks, the roof being then carried by the walls, as in an acid Siemens furnace. The hearth, or crucible of the furnace, is then padded with basic material, to a height above the slag line, as shown in fig. 160. The objection

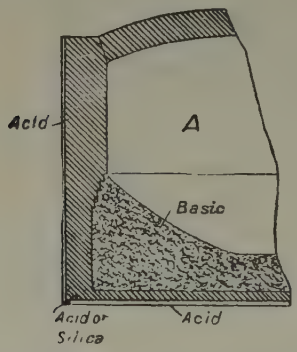


Fig. 160. — Silica Brickwork continued down to bottom of hearth to carry the weight of walls and roof. Hearth padded with basic material.

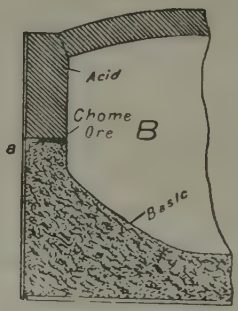


Fig. 161.—Silica Brickwork above the basic supported on angle iron, *a*, with Chrome joint between the two materials.

to this is that the working hearth of the furnace is somewhat restricted, and a furnace which, in acid work, would take 25 tons, will probably not take more than 20 tons; provided one is prepared to go to the extra first cost, and build larger furnaces, this system is probably the best as regards repairs, as in the event of the banks being cut away, if they are not fluxed quite to the Silica brickwork backing, there is no fear of roof or side walls giving way. Another method of relieving the basic material from the weight of the walls of the furnace, is to partly support the side walls, just above the basic material, by a stout angle iron, *a*, rivetted upon the inside of the furnace casing, as shown in fig. 161, and to make a joint of Chrome iron ore between the acid and basic materials. A method, originally used by Mr. Darby, of Brymbo, and shown in fig. 163, is one which has been very generally adopted, and is found to give very good results, and when the question of output for a given size of furnace is considered, perhaps better results than

any other. This, as will be seen from figs. 162 and 163, consists in carrying the weight of the roof on a long horizontal arch, so that at the point of contact there is no great pressure between the acid brickwork and basic material, and under these conditions, even without a Chrome joint, little or no fluxing takes place between the two materials.

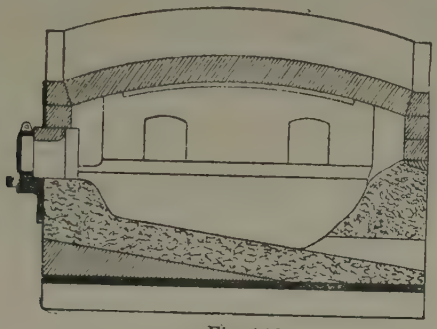


Fig. 162.

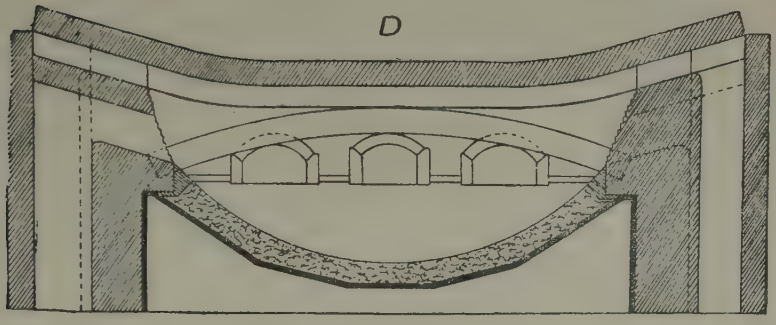


Fig. 163.

Preparing the Hearth.—In making the hearth or bottom of the basic Siemens furnace, several methods are in use. In some of the earlier furnaces the hearth was built up with basic bricks (see p. 59), made either by hand or in a hydraulic press, with tar as binding material, and the joints were then slurried with a mixture of basic material and tar; this was not found to give good results, as not infrequently if the bottom got cut away, large portions of it would lift, and a number of bricks float up into the bath of metal. Another method tried was ramming the entire bottom up with basic material and tar, as used for lining converters, and then gradually heating the furnace, first with a fire on the hearth, and then with the gas, until the entire mass was burnt hard. In this case, as with bricks, it was found practically impossible to burn the basic material hard through its entire thickness, with the result that if the bottom got cut away to any depth, to the partially burnt lower portion, large masses would lift. By far the best practice is to glaze the bottom on, as in the case of the acid furnace. It is usually best before starting to cover the iron bottom plates with two or three courses of Silica bricks,* and then a few inches of ramming of basic material mixed with tar; this is then well fired until burnt quite hard, when a thin layer of basic material, either dry or mixed with a little tar

* Magnesia brick may with advantage be used for larger furnaces, but are much more expensive.

and not exceeding an inch in thickness, is thrown into the furnace, levelled with the peel, and well glazed on. This is repeated until the bottom is built up to the required thickness and shape. To get the required thickness on the banks, basic bricks may be placed round the sides of the furnace, in a similar way to that shown in fig. 144, for an acid furnace, or a thicker layer may be rammed on. Burnt Magnesite has been used very successfully as a lining for Siemens furnaces, and this lining lasts much longer than an ordinary basic lining, but, owing to the high price, it has not been generally adopted, and it is probable that it is economical to use it only when situated so that supplies of Magnesite can be readily obtained. Magnesite bricks have been used and found most satisfactory, especially as a backing for the basic material, and expense is the only drawback. In America, in parts of the furnaces which are especially liable to be cut away, these bricks are very generally used, and if not directly exposed to the fluxing action of the slag, last for an indefinite time. Carbonate of Magnesia, containing about 98 per cent. of Carbonate, is used for making these bricks.

In some American works the practice is to put first a course of fire-bricks and then Magnesia bricks, and then glaze basic material on to these to form the hearth. In others the first course is fire-brick, then one course of Chrome bricks, then Magnesia bricks, and finally basic material.

Chrome iron ore has been used alone as a lining for basic furnaces, but partly on account of the cost, and partly owing to the difficulty of getting it to frit together and form a hard mechanically strong bottom, its use is practically confined to acting as a separating medium between silicious and basic material when one is resting directly upon the other. Bauxite has also been tried, but unless extremely pure is not sufficiently infusible, and, owing to its great shrinkage on intense heating, is liable to crack. Lime, which is the cheapest and most readily obtainable of all basic or neutral materials, is not suitable, partly on account of its great infusibility, and partly owing to the difficulty of keeping it for any length of time previous to use without slaking.

As a matter of actual practice, therefore, no material has been found so generally suitable as the burnt dolomite or basic material, as it is sufficiently infusible for the purpose, and at the same time sufficiently fusible to just frit together and form a hard mechanically strong bottom at Siemens furnace temperatures. It must be remembered that, from the chemical point of view, any of these so-called neutral materials—*i.e.*, materials that are inert or not readily acted upon, either by ferruginous or basic slags—would answer perfectly for the hearth of the furnace, the only thing required being a material to act as a crucible, which shall be infusible and unacted upon by highly ferruginous and calcareous slags, at the temperature employed, and so enable lime to be added to form a stable Phosphate. The tapping-hole in a basic Siemens furnace is made in a manner very similar to that in an acid Siemens, anthracite being placed at the back, but instead of fireclay and sand, a little basic material and tar are generally rammed into the hole, next to the anthracite, and the remainder made up on the outside with sand.

Details of Working.—The usual method of working is as follows:—The furnace being thoroughly hot, generally a little lime and ore are charged upon the bottom, then the pig-iron, with which a few shovelfuls of ore and lime are mixed from time to time, and, lastly, the greater portion of the scrap. In the case of very light scrap, a portion of this may be charged during the melting down, as in the acid process, but it is preferable to charge all the pig and scrap at the same time. The charge is then melted down, and when clear—*i.e.*, quite melted—addi-

tions of iron ore or non-silicious oxide from basic or oxide reheating furnaces, or any form of Ferrous or Ferric Oxide, free from Silica, are thrown in, with lime or limestone from time to time. The furnaceman, when the charge has been on the boil for some time, takes out small samples with the spoon, hammers them down, quenches, and bends them over until fracture takes place, and from the fracture and the condition of the slag is able to judge how the process is proceeding, and if more ore or lime is required. Although it is essential to maintain a basic slag, and also a fairly oxidising one during the early stages of the process, it is important that too much lime should not be added, both on the score of economy, and also to avoid getting a pasty slag; and it is equally important not to have too oxidising a slag, as otherwise the metal will be over-oxidised, very wild in casting, and probably red short when rolled. The great point which the furnaceman has to guard against is the removal of his Carbon before the Phosphorus, and this is especially so in the case of high Phosphoric charges, as there is often a tendency for the metal to go off the boil before the Phosphorus is oxidised to the required extent. If this happens it is only with the greatest difficulty that the last traces of the Phosphorus can be finally removed. If this should occur, the only thing to do is to add hematite pig-iron to the bath, and try to get the metal on the boil again. The probable reason why it is so difficult to remove Phosphorus after the Carbon has been oxidised is that there is no CO coming off from the bath to act as a mechanical stirrer, and bring the metal into intimate contact with the oxide and lime in the slag, by which the Phosphorus is oxidised, and unites with the lime to form a stable Phosphate of Lime. In working highly Phosphoric charges, as in the case of a very high Phosphoric pig-iron and small percentage of scrap, this removal of the Carbon before the Phosphorus is much more liable to occur than in working low Phosphoric pig and the usual amount of scrap, as the relation between the percentage of Carbon to the percentage of Phosphorus is so much lower in the former, and consequently the risk of removing the Carbon before the Phosphorus so much the greater. The furnaceman should never tap until he is satisfied from the examination of his samples that his Phosphorus is not more than ·05 per cent., as otherwise he may find an average sample from the heat when tapped gives over ·06 per cent. In some works a sample passer makes a rapid determination of Phosphorus by the Molybdate method, measures the precipitate in a very small tube of known size and compares it with a standard sample, this being an excellent check on the furnaceman.

Although the reactions taking place in the basic Siemens process are practically identical under different systems of working, the rate of removal of the metalloids may be made to vary within very wide limits. As Oxide of Iron does not readily flux with the basic bottom in the way it does with a silicious hearth, considerable quantities of Oxide can be placed on the bottom of the furnace before charging, and in the very early days of the basic Siemens process, the author believed that the rapidity of the working of charges might be greatly facilitated by adding a large proportion of the Oxide and lime or limestone required on the bottom of the furnace before charging the metal. By this method of charging, during the melting period, the metal runs down into a bath of molten basic Oxide, and the impurities are rapidly removed from one part of the charge while the other is melting, so that, when completely melted, the charge is nearly converted into steel. Although this was found to be the case under the special conditions of the experiments made, which were with very high Phosphoric pig-iron, it was also found that there was great liability to get the Carbon removed before

the Phosphorus. What probably happened was that as the metal melted little by little into the molten Oxide, the Carbon was oxidised very rapidly, and before the charge was entirely melted, there was practically a bath of carbonless and dephosphorised steel, and as further pig-iron melted down, this Phosphoric material mixed with the bath of practically carbonless iron. The result was metal comparatively high in Phosphorus and low in Carbon, and there was then great difficulty in removing the last traces of Phosphorus. With a low Phosphoric pig-iron, where the proportion of Carbon to Phosphorus would have been higher, much better results could have been obtained, and even with high Phosphoric iron, containing 2·5 and 3·0 per cent., some hundreds of tons of excellent steel were made.

The removal of Phosphorus before the Carbon in the Siemens furnace is largely a question of temperature, and it was found in practice that the temperature of the furnace when working on these lines could not be controlled sufficiently to insure the removal of the Phosphorus before the Carbon, with the result that the production of low Phosphorus steel regularly could not be depended upon, and more regular results were obtained by adding less Oxide before charging, and finishing the charges by addition of Oxide after the bath was melted. In some works no Oxide is charged with the metal, but the usual practice is to add some, the amount varying with the composition of the charge. It is not possible to lay down any definite rule as to the amount of Oxide which should be added with the charge, as it is really a matter of experiment to find the proportion that gives the best practical results, both as regards rapidity of production and quality of product for a given composition of charge.

When the furnaceman, by examination of his samples, is satisfied that the Phosphorus and Carbon are removed to the required degree, he at once gets ready to tap. A few half pigs of hematite iron are added to bring the metal to the boil again, and the tapping-hole is opened by driving a steel bar through it as described in the acid process. The Ferro-Manganese is always added in the ladle, usually broken to the size of peas, and thrown on the stream of metal as it passes from the furnace. If added in the furnace, there is great danger of Phosphorus passing back from the slag to the metal.

Pig-iron and Scrap.—The pig-iron used should be as low as possible in Silicon and Sulphur, fairly high in Manganese, and Phosphorus may vary from 0·100 to 2·00 per cent., or even 3·00 per cent., although a pig-iron not exceeding 1·5 per cent. is much to be preferred, if it is desired to produce regularly a steel of high quality.

Unlike the basic Bessemer—where a certain amount of Phosphorus is required to maintain the heat of the bath—here, where the temperature is maintained largely by external means, the lower the percentage of Phosphorus in the pig-iron used, the greater the ease and regularity with which this impurity can be removed. The actual charge of pig-iron and scrap will vary with the quality of the materials available.

In many works in England, a pig containing Phosphorus about 1·75 per cent., Silicon under 1·00, Sulphur, ·05; Manganese, 1·5 to 2·00, and Carbon 3·50, is very generally used, and about 25 to 30 per cent. of wrought iron and steel scrap is charged with this pig. More scrap may be used if available; but, when working on a large scale, it is not generally possible to obtain more at a price which will pay in this country.

One great advantage of the basic Siemens over the acid process, is that miscellaneous scrap, either wrought iron or steel, containing a percentage of Phosphorus which would render it useless for acid Siemens practice, may be used, and, consequently, this can be obtained, often at a lower price than selected steel scrap, and a larger proportion can be used in the charge. In

some cases, in districts where large quantities of scrap are obtainable, as much as 70 to 80 per cent. is melted in each charge, and then very rapid working is possible, as much as three to four heats being melted in the twenty-four hours; in these cases, the furnace becomes really only a scrap melting furnace, the whole of the impurities being practically removed during the melting period so that when once the bath is clear it is ready to tap, provided it is sufficiently hot. This practice is followed in some parts of the Continent by small works with one or two furnaces, in districts where large quantities of scrap can be cheaply obtained; but commercial conditions do not permit of its being carried out in England to any extent.

The following analyses (Table xxxii.) made by the author from a number of charges, illustrate the removal of impurities in the basic Siemens furnace during melting, when charging varying quantities of ore with the pig-iron; charges B may be taken as fairly typical of normal working for high Phosphorus pig, about 2 cwts. of ore or oxide being charged per ton of metal with the pig-iron. For a low Silicon and Phosphorus charge, of course, the amount of ore would be considerably reduced to obtain the same percentage of removal of the impurities:—

TABLE XXXII.—Showing the Removal during Melting of Metalloids in Basic Open Hearth under Different Conditions of Working.

Composition of Charge. Calculated. 20 per cent. Scrap		When Melted.						
		A. 1 Cwt. of Oxides per Ton of Metal charged with the Pig-iron.				B. 2 Cwts. of Oxides per Ton of Metal charged with the Pig-iron.		
		1	2	3	4	1	2	3
Carbon,	3·00	2·38	2·40	2·29	2·49	1·89	1·69	1·59
Silicon,	1·40	·069	·060	·046	·093	·046	·074	·046
Phosphorus,	2·80	2·67	2·43	2·44	2·48	1·588	1·64	1·32
Manganese,	1·80	·546	·89	·600	·66	·100	·04	·08
Sulphur,	·060	·06	·052	·032	·071	·096	·104	·096
Same quantity of Lime charged with heats 1, 2, 3, 4.								
Composition of Charge. Calculated. 20 per cent. Scrap.		When Melted.						
		C. 3 Cwts. of Oxides per Ton of Metal charged with Pig-iron.				D. 4¾ Cwts. (practically the whole quantity required) of Oxides per Ton of Metal charged with the Pig-iron.		
		1	2	3	4	1	2	3	4
Carbon,	3·000	1·00	1·300	·670	0·900	0·140	0·120	0·150	0·130
Silicon,	1·36	·037	·040	·037	·040	·090	·020	·016	·046
Phosphorus,	1·70	·600	·640	·705	·960	·134	·088	·122	·081
Manganese,	1·14	·288	·288	·200	·140	·288	·200	·140	·160
Sulphur,	·140	·139	·140	·120	·107	·127	·160	·150	·150
Same quantity of Lime charged with heats 1, 2, 3, 4.									

It will be noted that, when a large quantity of ore was charged with the metal, the bath was practically decarburised and dephosphorised when melted.

Considerations Respecting Slag.—The most essential conditions for the successful working of the basic Siemens process are :—1. The maintenance of a sufficiently basic slag to prevent the dissociation of the basic Phosphate of Lime by the reducing action of the Carbon in the metal bath, and of the Silica in the slag. 2. To prevent fluxing of the bottom by a too silicious slag. 3. To maintain a slag sufficiently fluid, so that it may be brought into intimate contact with the metal. 4. To keep the slag sufficiently, but not too oxidising, to do the necessary chemical work during the early stages of the process, and to finish with as neutral a non-oxidising slag as possible. This latter is very important, as an oxidising slag at the end of the operation means over-oxidised metal, which leads to wild heats, and to finished steel which is red short and mechanically defective. Basicity of the slag is obtained by the lime or limestone additions, and by the basic material which is taken up from the lining, although one great object of the lime additions is to prevent the latter as much as possible. The fluidity is due largely to the Manganese oxidised, the Oxide of Iron formed during melting, and added as iron ore, and any other small quantities of bases, added as impurities in the ore and lime, which unite with the Silica present. It is mentioned by Campbell,* who gives a large number of analyses from different charges with varying percentages of Phosphorus to support his contention, that as the Silica decreases the FeO increases, and that under similar conditions low Silica means high FeO, and consequently more complete dephosphorisation.

He suggests that the reason for this automatic adjustment between the Silica and the Oxide of Iron is due to a struggle to attain a certain degree of fluidity, and acting in obedience to this tendency, Silica and Oxide of Iron replace each other. Whether the more complete dephosphorisation is due simply to increased fluidity or to the oxidising power of the slag, Campbell considers has not been decided ; but it seems probable it is due to both these causes, as greater fluidity means more intimate contact with the metal, the larger percentage of Oxide means a more energetic, oxidising slag, and less Silica means a relatively more basic slag, with greater power of retaining the Phosphorus in the form of stable Phosphate of Lime. We thus have the Oxide of Iron in the best possible condition to do its work of oxidation, and a slag rich in lime ready to combine with this Phosphorus when oxidised, which broadly may be taken as the functions of these two bodies in basic Siemens practice. In fact the successful working of the process and production of steel of regular quality may be said to practically depend upon maintaining the proper adjustment between the oxidising bases in the slag on the one hand, and the non-oxidising bases on the other, and it is here that the skill of the melter shows itself. The following are some typical analyses of basic slags from basic Siemens furnaces, taken from an average of a large number of analyses. The Phosphoric acid will vary with the amount of Phosphorus present in the original charge, but the Silica and lime will be relatively about the same, as the amount of lime added depends far more upon the Silicon content of the charge than the Phosphorus content, and the Silicon varies comparatively little except in cases where almost entirely scrap charges are being worked. Thus in actual practice the additional amount of lime it is necessary to add to a charge containing 2 per cent. Phosphorus, as compared with a charge with 1 per cent., does not greatly affect the relative percentages of Silica and lime in the two slags.

* *Trans. American Inst. of Mining Engineers*, vol. xxii., pp. 445 and 446.

The following may be taken as fair average composition of finishing slags :—

Composition of Basic Slags Taken from a Large Number of Casts.

Silica.	Oxide of Iron.	Oxide of Manganese.	Lime.	Magnesia.	Phosphoric Acid.
12·89	16·85	7·54	41·4	4·70	11·2

Campbell,* in his paper on the open hearth process, gives the following average composition for slags :—

Silica.	Oxide of Iron.	Phosphoric Acid.	Oxide of Manganese.	Lime.	Magnesia.
10·50	17·65	13·06	8·75	40·84	5·04
11·50	15·57	13·12	10·22	40·02	5·47

The final slag should not contain more than 16 to 17 per cent. of Oxide of Iron, as more than this usually means undue waste and liability to over-oxidised metal.

Manufacture of High Carbon Steel in Basic Siemens Furnace.—When using Phosphoric pig, &c., in the basic open hearth, it is difficult to completely remove the Phosphorus before the Carbon and finish with a bath of any required content of Carbon, and it is not possible to pig back by charging hematite pig-iron on the banks of the furnace to give the percentage of Carbon required, as in the acid process, as this would reduce phosphoric acid from the slag, and the Phosphorus would pass back into the metal. If it is desired to make high Carbon steel, the usual practice is to recarburise the metal outside of the furnace, and so keep the slag and Carbon out of contact.

Darby Recarburising Process.—Mr. J. H. Darby, of Brymbo, some years ago, taking advantage of the fact that molten steel rapidly absorbs Carbon when brought into contact with it, devised a special method of making steel of any required Carbon percentage by intimately mixing Carbon with the molten metal as it leaves the furnace.

The arrangement used is shown in fig. 164. It consists of a hopper with an adjustable orifice, in which the required weight of Carbon is placed and allowed to fall in a stream into the subsidiary perforated vessel, A, which is suspended over the casting ladle, and into which the steel flows on its way to the ladle. The delivery of the Carbon can be regulated by varying the opening in the hopper, and only small quantities of Carbon and steel coming together at one time, there is no danger of causing a boil in the ladle, and intimate admixture of Carbon and steel is insured. The whole of the Carbon is not absorbed, there being a loss of about 20 per cent., which must be allowed for in calculating the amount required for any particular charge.

The Carbon used should be as dense as possible and free from Sulphur, anthracite coal or dense, hard, pure coke giving good results.

Steel is now generally carburised by adding anthracite coal in the ladle, or throwing it on the stream of metal as it passes into the ladle; in this way the carburisation can be fairly well controlled, but care must be taken to add the Carbon before the slag passes into the ladle or it is liable to cause the metal to boil.

The Elimination of Sulphur.—Under the normal conditions of working the basic Siemens process, the removal of Sulphur is very variable—in some charges, considerable amounts being removed, and in others, worked apparently under the same conditions, none at all, and even an increase is sometimes observed. It is advisable, therefore, if a regular low Sulphur steel is desired, to start with low Sulphur pig, and a pig containing also a fair percentage of Manganese.

* *Trans. American Inst. of Mining Engineers*, vol. xxii., p. 440.

The exact part played by Manganese in the elimination of Sulphur in the basic Siemens may not be clearly understood; but that it does play an important part has been proved without doubt, and the addition of Spiegel

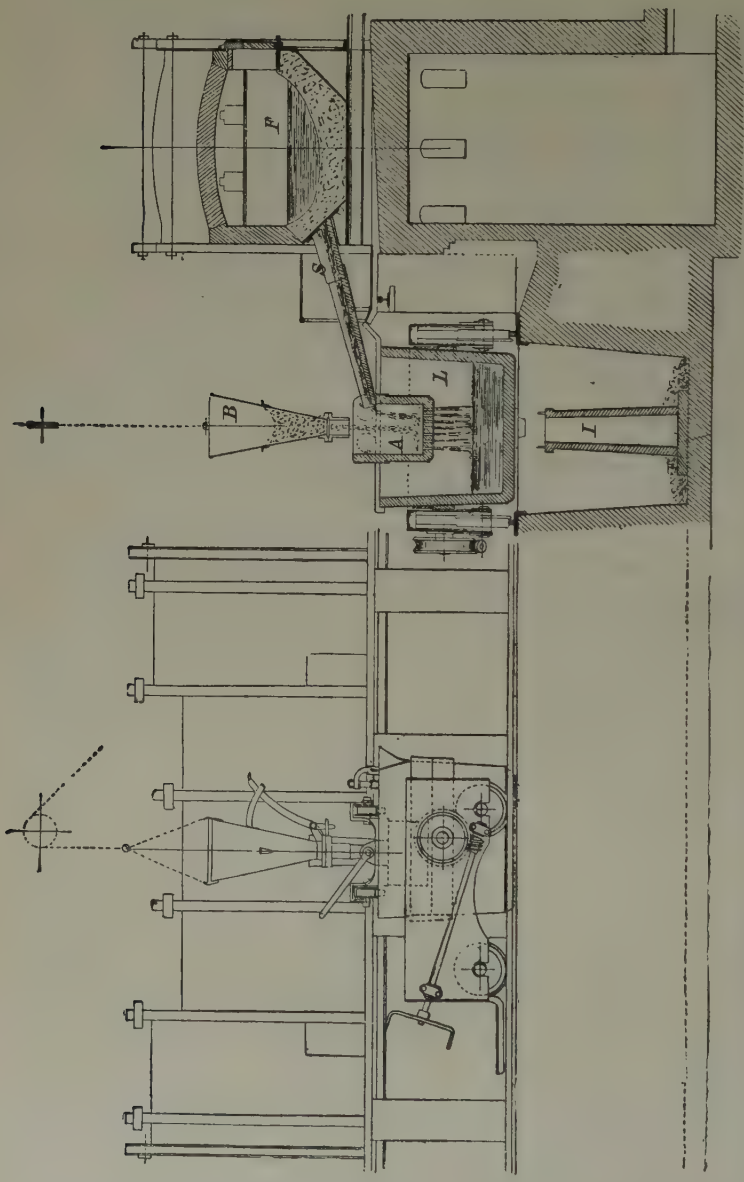


Fig. 164.—Darby Recarburising Apparatus—B, Hopper containing Carbon; A, subsidiary vessel for mixing Carbon and steel before entering ladle; L, ladle; I, ingot mould.

The subsidiary vessel, A, is now rarely used, sufficient intimate admixture and absorption of the Carbon being obtained by allowing the Carbon to fall in a fine stream upon the metal as it flows from the furnace into the ladle.

or Ferro-Manganese at the end of the charge before tapping is generally followed by a distinct reduction of Sulphur. It is probable that the Sulphur passes into the slag in the form of Sulphide of Manganese in the same way

as it was shown by Massenez* to do in a metal mixer in the presence of Manganese. The amount of Sulphur which can be removed by Manganese *additions* is, however, very limited, as, if too much carburising metal is added, Phosphorus will be reduced from the slag and pass back into the metal, and the steel will be high in Phosphorus. It is better, therefore, to melt a certain proportion of manganiferous pig-iron with the charge, or to add manganiferous ores to the bath to maintain a fair percentage of Manganese Oxide in the slag, which is alternately reduced and oxidised, and, in passing backwards and forwards from the metal to the slag, certainly tends to remove the Sulphur, especially when a very basic slag is employed. Campbell has shown in his paper already referred to that, other things being the same, a highly calcareous slag distinctly tends to the more complete removal of Sulphur, and, broadly, the more basic the slag the larger the percentage of Sulphur removed. Here, again, the results are very variable, and it seems impossible to rely upon the removal of a definite percentage of Sulphur, even when working under the same conditions as regards slag and metal.

Various methods of desulphurising molten metal before or during conversion into steel have been suggested, the essential conditions in all apparently being a fluid basic slag and intimate contact between metal and slag.

Rollet claimed to be able to remove 99 per cent. of the Sulphur by melting pig-iron with large excess of lime, and from $2\frac{1}{2}$ to 4·8 per cent. of Fluorspar, so that the slag contained less than 2 per cent. of Silica. Under conditions of low temperature, Oxide of Iron, as shown by the puddling and Bell and Krupp washing processes, is capable of removing very considerable quantities of Sulphur, varying from 50 to 90 per cent., according to the percentage present, and other conditions. The old Henderson process of pouring molten pig-iron on to the hearth of a furnace covered with fine Oxide of Iron and Fluorspar, removed considerable quantities of Sulphur, and the Heaton process of pouring molten iron on to nitrate of soda, according to the analyses of Miller and Snelus, was most effective in removing it. As much as 77 per cent.† of the Sulphur can be removed by pouring molten iron on to a mixture of soda ash and ground limestone

The removal of Sulphur in the metal mixer by Manganese as MnS has already been referred to, and this is probably the most satisfactory method of desulphurising large quantities of molten metal, especially if manganiferous metal for mixing is available.

With the exception of the mixer, practically all the above methods depend upon the action of a fluid basic, and more or less oxidising, slag.

The use of alkaline salts has been shown by Messrs. Ball and Wingham to remove considerable quantities of Sulphur, and their conclusion that the absence of oxidising agents is desirable, seems to be confirmed by the results obtained in electric furnaces,‡ where it is found that a slag containing a very high percentage of lime and practically free from Oxides of Iron gives the best results.

Further experience with the basic open hearth process has demonstrated that to desulphurise, it is best first to dephosphorise as much as possible with a fairly oxidising slag, and then to add excess of lime, with fluor spar to increase the fluidity of the slag, towards the end of the operation; no further additions of oxide should be made, so that the finishing slag may contain the maximum amount of lime and the minimum of Oxide of Iron. The percentage of lime which a basic open hearth slag can be made to carry and still be sufficiently fluid is limited by the temperature available, and, consequently, the very complete removal of Sulphur is attended with considerable practical difficulties. This elimination of Sulphur is costly, as it

* *Iron and Steel Inst. Journ.*, 1891, vol. ii., p. 76.
† *Ibid.*, 1892, vol. ii., p. 257.
‡ See chap. xi., p. 279.

is essential that the metal should be kept in the furnace under a very basic slag for a considerably longer period than would be necessary for the removal of Phosphorus to the usual limits required for structural steel, which entails a large consumption of fuel and lime and reduces the output of finished product in a given time. Probably a mixture of soda ash and finely-ground lime would give excellent results, the soda ash giving fluidity and basicity, and molten metal poured upon such a mixture, under proper conditions, would be largely desulphurised, the chief objection being the question of cost.

The Saniter Process.—The method of desulphurisation proposed by Saniter, has given very good results, and is now in use in several steel works.

It is based on the use of Calcium Chloride in conjunction with lime, and, although the exact reactions by which the Sulphur is removed are not clearly understood, the researches of Stead * and others have thrown some light on the subject, and it seems probable that an oxychloride of lime of indefinite composition is formed, which enables a slag of great fluidity and at the same time of great basicity to be brought into intimate contact with the fluid metal.

The process may be carried out in two ways—(1) by treating the molten cast iron in a ladle as it comes from the blast furnace before it is cast into pigs; (2) by desulphurising the molten metal during its conversion into steel in the basic open hearth or basic Bessemer converter.

In the first case, a fusible mixture is made by grinding together Calcium Chloride, Lime, Fluorspar, and Limestone in the proportions which are found to give a slag which is fluid at the melting point of cast iron.

This mixture is placed on the bottom of the ladle, and the molten iron run upon it, when it gradually melts and rises through the bath of molten metal, and, in so doing, removes as much as 66 per cent. of the Sulphur present from iron containing 0·20 per cent. Saniter recommends the following mixture for each ton of pig-iron :—

Dry Calcium Chloride, 9 lbs. Fluorspar, 9 lbs. Lime, 15 lbs. Limestone, 8 lbs.

In desulphurising in the basic open hearth or Bessemer processes dry Calcium Chloride must be added during the working of the charge, with the usual lime additions, care being taken that the latter are added in sufficient quantity to give a slag containing over 50 per cent. of lime. It seems probable that, given a basic slag with this percentage of lime, which, at the same time, retains its fluidity, the dephosphorisation, as well as desulphurisation, should be greatly facilitated, and the following analyses† of steel charges, made from pig-iron of very varying composition, distinctly support this view :—

TABLE XXXIII.

	1.		2. Cleveland.		3. Basic Cinder Pig.		4. Hematite Pig.	
	Pig-iron.	Steel.	Pig-iron.	Steel.	Pig-iron.	Steel.	Pig-iron.	Steel.
Carbon, .	...	0·12	...	0·25	...	0·22	...	0·110
Silicon, .	0·28	Trace	1·50	Trace	0·5	Trace	0·70	Trace
Sulphur, .	0·96	0·07	0·25	0·025	0·22	0·018	0·06	0·016
Phosphorus,	0·75	0·026	1·50	0·030	3·50	0·036	0·06	0·008
Manganese,	0·30	0·47	0·70	0·45	1·00	0·40	0·20	0·110

No. 1 was pig-iron especially selected, containing an abnormal quantity of Sulphur, to show how completely it could be removed, but the other pig-irons, considering the low percentage of Silicon and Manganese, are fairly typical of common iron, and in each case the Sulphur removal is very complete. It may seem doubtful if it is not better and cheaper to make a proper basic pig-iron low in Sulphur by addition of Manganese ores, &c., in the blast furnace, rather than throw the responsibility of removing this objection-

* *Iron and Steel Inst. Journ.*, 1892, vol. ii., p. 260. † Supplied by Mr. Saniter.

able constituent upon the steel maker, and in the author's opinion this is the correct thing to do. But even then there will always be some iron made with high content of Sulphur, and in such cases, or where the local conditions are such that a low Silicon and low Sulphur iron cannot be made economically in the blast furnace, the Saniter process comes to the rescue, and enables high-class steel to be made when it would otherwise be impossible. In cases, too, where fuel for gas production is of inferior quality, so that the metal in the Siemens furnace is liable to take up Sulphur during the process of manufacture, the addition of comparatively small amounts of Calcium Chloride would probably greatly reduce this liability of the metal to absorb Sulphur, if it did not altogether prevent it. The process is not of course applicable for working in an acid-lined furnace, as a slag containing over 50 per cent. of lime is essential; but hematite pig-iron for acid work can of course be desulphurised in the ladle before charging into the furnace. It has been urged against the process that anything like the complete removal of the Sulphur—*i.e.*, to ·03 per cent. or less—greatly increases the length of time required to work a charge of steel, and so reduces the output, and there is certainly some truth in this, although this will greatly depend upon the quantity of Calcium Chloride mixture added, and if this is added in sufficient quantity to maintain a *strongly basic fluid slag* to the end of the operation, the delay in working should not be a serious objection. One curious effect of the Calcium Chloride and Fluorspar appears to be that they considerably reduce the solubility in citric acid of the Phosphoric acid in the slag, an important point, as the value of the slag as a fertiliser depends largely upon this solubility.

Mr. W. G. Burman * has investigated this question by adding varying quantities of Fluorspar (from 1 to 10 cwts.) to the slag in 18-ton steel charges, and the following table gives the results obtained as regards the solubility of the Phosphoric acid with and without Fluorspar:—

TABLE XXXIV.

With the Addition of Fluorspar.				Without Fluorspar.		
Amount of Fluorspar used.	Total Phosphoric Acid.	Soluble Phosphoric Acid.	Solubility.	Total Phosphoric Acid.	Soluble Phosphoric Acid.	Solubility.
Cwts.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
2	17·66	7·42	42·0	15·72	13·3	84·6
7	15·37	2·56	16·6	14·93	13·18	88·2
1½	15·81	8·44	53·3	15·75	14·30	90·8
6	15·81	3·45	21·8	17·07	13·33	83·9
10	13·43	0·78	5·8	16·26	14·12	86·8
5	15·84	3·82	24·1	15·75	13·43	85·2

Hematite and Low Phosphorus Pig-Iron.—In this country most of our Phosphoric ores contain a somewhat high percentage of Phosphorus, and consequently comparatively little or no pig-iron is produced with Phosphorus just outside the hematite limit—say, from 0·100 to 0·500—and our basic steel makers have generally to deal with pig-iron containing at least 1·5 per cent. of Phosphorus, and frequently more. Unless they are prepared to pay an extra price, they have also to take fairly high Silicon. In some parts of the Continent, and in America, where low Phosphoric ores exist and pig-iron with about 0·25 per cent. of Phosphorus is obtainable, the task of the steel maker is a comparatively easy one, as dephosphorisation is

* *Iron and Coal Trades Review*, January 9, 1903, p. 94.

practically always complete *long before the bath is decarburised*, so that there is really no danger of any appreciable amount of Phosphorus being left in the steel when the final Carbon has been removed, and a very regular low phosphorus steel is the result.

One direction in which the basic process has developed to a small extent when an exceptionally pure material is required for electrical and other purposes is the working of hematite pig-iron charges in the basic Siemens. As it is difficult to get English hematite iron low in Silicon without being high in Sulphur, and as high Silicon pig causes endless trouble in a basic furnace, it is not only advisable, but practically necessary, to use what may be termed a basic hematite—that is to say, a pig made from hematite ores with Manganese ores added, so that the pig-iron is low in Silicon and Sulphur and contains about 2 per cent. of Manganese. Considering how easily such pig-iron is treated in the basic furnace, the small extra cost of working the process compared with the acid, and the extraordinary purity and regularity of the final product, it is somewhat surprising that more acid steel makers have not put basic linings into their furnaces to treat pig-iron of this description, and made special arrangements with the blast furnace people for the production of a suitable pig-iron. Below are given the analyses of samples taken from a hematite charge during every half-hour, and they show very clearly that almost directly the bath is melted the Phosphorus is reduced below the average of that present in high-class acid steel in the finished state.

TABLE XXXV.—Chemical Analyses of Steel Samples taken at Intervals of 30 Minutes, during the Working of a Hematite Charge, in a Basic Siemens Furnace producing Low Carbon Steel.

Nos.	Carbon.	Silicon.	Sulphur.	Phosphorus.	Manganese.	Arsenic.
1	1·800	0·008	0·032	0·054	0·391	trace
2*	...	...	...	...	...	...
3	1·740	0·006	0·037	0·046	0·380	trace
4	1·451	0·006	0·029	0·023	0·340	0·004
5	1·461	0·007	0·038	0·025	0·340	0·002
6	1·234	trace	0·030	0·013	0·327	0·004
7	1·161	,,	0·030	0·016	0·290	trace
8	0·927	,,	0·025	0·013	0·293	0·004
9	0·912	,,	0·036	0·010	0·236	trace
10	0·871	,,	0·040	0·008	0·270	0·002
11	0·690	,,	0·038	0·009	0·220	0·004
12	0·540	,,	0·032	0·006	0·280	trace
13	0·434	,,	0·030	0·009	0·270	,,
14	0·342	,,	0·032	0·006	0·270	0·003
15	0·160	,,	0·037	0·008	0·240	trace
16	0·145	,,	0·041	0·006	0·250	,,
17	0·102	,,	0·037	0·008	0·230	,,
18*	...	...	...	...	...	...
19	0·070	trace	0·035	0·008	0·244	trace
20*	...	...	...	...	...	...
21	0·097	trace	0·030	0·007	0·220	0·004
22*	...	...	...	...	...	...
23	0·108	trace	0·033	0·005	0·240	trace
24	0·101	,,	0·034	0·004	0·217	,,
25	0·078	,,	0·033	0·007	0·217	,,

* Nos. 2, 18, 20, and 22 were not analysed.

The samples were kindly supplied by Mr. Darby, of Brymbo, for the late Sir Wm. Roberts-Austen's experiments, in connection with the Alloys Research Committee, and the analyses were made by the author. In view of the fact that our own hematite ores are rapidly becoming exhausted, and that many of the large Spanish deposits are also, to a very large extent being depleted, it is a question worthy of the serious consideration of our iron and steel manufacturers, whether it would not pay better to make a basic pig from part hematite and part native ores, to contain, say, not more than 0·50 per cent. of Phosphorus, and to work such pig in basic furnaces in preference to hematite pig by the acid process. There can be no reasonable doubt that starting with such a low Phosphoric pig-iron, a steel could be produced which, both as regards regularity of chemical composition and mechanical properties, cou'd hold its own for all structural purposes with any steel produced in the world.

As things are at present, however, it is often difficult to obtain such pig-iron fairly low in Phosphorus, and low in Silicon and Sulphur, although there is no difficulty in obtaining *high* Silicon pig low in Sulphur. To meet this difficulty many attempts have been made at preliminary refining previous to treatment in the basic Siemens, some proposals being to simply desiliconise, and others to both desiliconise and dephosphorise.

The simplest way of desiliconising is to blow the molten metal from the blast furnace for a few minutes, generally about six minutes, in an acid-lined Bessemer converter, and then transfer in the molten state to an open hearth or Siemens furnace to dephosphorise and decarburise. This method of working is practised in some German works, but the waste in Bessemerising and cost of maintaining two plants has prevented its being at all generally adopted. At some works with which the author was connected some years ago, experiments were made in this direction, but after trials extending over a considerable time, they were abandoned, as it was found cheaper to pay a higher price for specially-selected pig-iron.

The processes which seem to offer the best promise of success are some modifications of the washing process of Sir Lowthian Bell, by which the iron can be largely desiliconised, and also, to a considerable extent, dephosphorised, by the action of an oxidising slag at a comparatively low temperature without appreciably removing the Carbon.

The Talbot Washing Process.—In 1892, Mr. Benjamin Talbot introduced a new washing process for the treatment of the very silicious irons of Alabama, which consisted in running the pig-iron from blast furnace cupola or mixer through a bath of molten basic slag, obtained from an open hearth furnace. The slag (from an open hearth furnace) was run into a basic-lined vessel, and molten iron was poured in a thin stream through this, and after being allowed to stand for a short time was either taken in the molten condition to an open hearth furnace or cast into moulds, and then charged into the furnace in the solid state. The slag from a finished heat of steel was found to be sufficiently oxidising to remove the Silicon and also part of the Phosphorus, and the heat developed by the chemical reactions was sufficient to maintain the metal in a fluid condition. If further oxidation was required, fluid Oxides or finely-divided solid Oxides were run into the containing vessel with the slag. Very excellent results were obtained by this process, but owing to the readiness with which low Silicon, Sulphur, and Phosphorus iron can be obtained in the States, it has not been used to any extent.

Krupp's Dephosphorising Process.—Another process depending upon the removal of impurities by fluid Oxides, is the Krupp washing process, which consists in running molten iron from a cupola into an open hearth furnace, the hearth of which is inclined and revolves, and in fact is somewhat similar to the old Pernot furnace. The hearth of the furnace is

lined with red ore by packing in small and large lumps, and thoroughly glazing the whole by heat. This hearth section is on a carriage, and can be removed when required. It is revolved by a steam engine, three or four times per minute, during heating up, and when the hearth is ready 700 to 800 lbs. of ore are charged and well heated. With very Phosphoric pig-iron more ore is added up to, say, 1,000 lbs., and if the iron is silicious some lime additions are made.

When the ore is raised to a white heat, melted pig-iron is run from the cupola, and the hearth rotated at a rate of about 10 or 11 revolutions per minute. After two or three minutes a vigorous reaction takes place, which lasts for about two minutes, when the bath becomes quieter, and the Carbonic Oxide begins to escape. If it is wished *not* to decarburise, the metal must be tapped at once, but if it is desired to carry dephosphorisation further, a little Carbon will necessarily be removed during the process. The whole operation up to the beginning of the evolution of CO gas lasts five minutes, and for the more complete dephosphorisation eight to ten minutes, the tapping taking a further three minutes. The dephosphorised metal is then transferred to an ordinary open hearth furnace, in which three heats can be made in twenty-four hours, using the dephosphorised metal without scrap.

The pig-iron should contain about 1·0 per cent. Manganese, not above 1·0 per cent. Silicon, and should be as high as possible in Carbon. The following are several analyses of metal samples taken before and after the dephosphorising, by which it will be seen that Carbon is not appreciably removed :—

		Before Treatment.	After Treatment.
1.	Carbon,	3·990	3·75
	Phosphorus,	0·632	0·132
2.	Carbon,	3·810	3·560
	Phosphorus,	0·450	0·108
3.	Carbon,	3·170	3·020
	Phosphorus,	1·220	0·300

The Carbon, after treatment, is all combined, and the fracture of the refined iron is white.

This process has been worked more or less as a secret process, and very little is known as to the yield, output, and costs of manufacture; but there seems no reason why a preparatory furnace on this principle without any revolving hearth, but worked at a low temperature to dephosphorise and desiliconise, should not play an important part in the future of the basic Siemens process, especially when dealing with very Phosphoric and irregular irons; although, of course, it would be better to do the whole operation in one furnace if possible, if equal rapidity of production and regularity of product could be ensured. In America a very pure material is obtained by treating hematite iron by this or a similar process, and the so-called "washed iron" is largely imported into this country and used to replace Swedish irons when very pure metal is required. Two analyses gave the following results :—

Carbon,	3·05	3·00
Silicon,	0·0097	0·010
Sulphur,	0·0027	0·0065
Phosphorus,	0·0077	0·0085
Manganese,	0·147	trace.

Modifications of Open Hearth Practice.—Many attempts have been made with more or less success to increase the rapidity of working in the Siemens processes, both acid and basic. Fluid blast furnace or cupola

metal has been repeatedly tried, and although the results obtained by different people were promising, this method of working until comparatively recently has not been generally adopted. It is somewhat difficult to arrive at the causes which militated against the use of molten metal, especially in the basic furnace, as although no doubt the destruction of bottoms is a serious matter, and the increase in output is not very great, the increase in yield is undoubted. Mr. James Riley,* as the results of some experiments in acid furnaces, stated that this destruction of the furnace bottom had been greatly exaggerated, and that with respect to economy of working, increased output, yield, etc., he had obtained good results. As regards the speed of working charges in the acid furnaces, there is little, if any, gain, as during the melting period, in ordinary working, a large amount of purification is effected; but there is a considerable gain both as regards labour and time in charging. In basic Siemens, where oxidising additions can be put on the bottom first, and more or less melted before the metal is poured into the furnace, the speed of working the charges is undoubtedly increased, but the wear and tear on the bottom is great. In the Southern States of America experiments were made by Talbot in 1893 on pouring molten metal into a bath of molten Oxide in a basic Siemens furnace, but owing to the very violent reaction, which rapidly destroyed the furnace bottom, they were not a practical success.

One reason why liquid metal was not years ago generally used in basic open hearth practice was that the early experiments were usually made with direct blast furnace metal, which was liable to vary considerably in temperature and in the content of Silicon. Under the best conditions the percentage of Silicon was always high, and this, with the varying temperature, was very destructive to the furnace hearth. Even when cupola metal was employed, the Silicon was always *comparatively* high, and the cost of melting had to be added to the cost of furnace repairs. The modern practice in basic open hearth works having a large output, is to pass the metal first through a large basic-lined *gas-fired* mixer, so that small additions of lime and oxide can be made, and the metal very largely desiliconised and to some extent desulphurised. By this means metal, uniform both as regards temperature and composition, is obtained, the Silicon is reduced to ·5 per cent. or less, and the wear of the furnace hearths is greatly decreased. When working with low Sulphur and low Silicon mixer metal, the output of the open hearth furnace is increased by about 30 to 40 per cent., and with fairly high Sulphur metal by 15 to 20 per cent., compared with furnaces melting cold pig-iron, or one and a-half to two extra charges per furnace per week; the yield is also increased by at least 5 per cent., and in good practice every 100 tons of molten metal charged should yield from 100 to 103 tons of ingots.

Bertrand-Thiel Process.—This process consists essentially of the use of two Siemens furnaces in combination, one known as the primary and the other as the secondary furnace. Pig-iron, Oxides, and limestone are charged into the primary furnace, and scrap and limestone in the secondary furnace. The charge in the first furnace is desiliconised, partially dephosphorised, and to some extent decarburised during melting, and after about 4½ hours is transferred to the secondary or finishing furnace, either by means of a runner or a ladle, special care being taken to keep the silicious Phosphoric slag from passing into this furnace with the metal. In this secondary furnace are scrap, limestone, and Oxides heated to a very high temperature, and when the metal is run upon these materials in a heated state, a very vigorous

* *Iron and Steel Inst. Journ.*, 1900, vol. i., p. 22.

reaction takes place, and the entire charge is converted in about 2¼ hours. In the earlier results published the dephosphorisation and decarburisation took place more or less simultaneously, with the result that Carbon and Phosphorus in the metal when tapped from the primary furnace were present in about equal percentages. From a large number of analyses given by Mr. Bertrand * as representing later work when working pig-iron containing 3·8 per cent. Carbon, 1·6 per cent. Phosphorus, 1·0 per cent. Silicon, and 1·00 per cent. Manganese, it appears that Phosphorus can be largely removed before the Carbon, and the following may be taken as representing the composition of the metal when run from the primary furnace :—

	Carbon.	Phosphorus.	Manganese.	Silicon.
1, . .	2·35	0·300	0·053	0·107
2, . .	2·35	0·432	0·002	0·163
3, . .	1·54	0·430	0·061	0·046
4, . .	2·12	0·589	0·052	0·102
5, . .	2·12	0·204	0·056	0·032

It will be seen that with 2·0 per cent. of Carbon the Phosphorus varies from ·20 to ·60 per cent., and is on an average about ·40 per cent. Metal of this composition can be readily dealt with in the finishing furnace. This removal of the Phosphorus before the Carbon is due to working the primary furnace at as low a temperature as possible, and with a highly basic slag. The results obtained with two experimental heats of metal containing 2·5 per cent. Phosphorus and 3·8 per cent. Carbon showed that the metal contained 1·20 per cent. Carbon and 0·55 per cent. Phosphorus when tapped from the primary furnace. It is considered that this percentage of Carbon and Phosphorus is suitable for taking direct to the finishing furnace, although it has been suggested that Carbon may be increased by recarburising on the way. This possibly could be done, but it introduces another operation which is objectionable, and it would probably pay better to work a lower Phosphorus pig-iron rather than attempt to recarburise should this be necessary. The present practice in the Bertrand process is to take fluid metal from the mixer, blast furnace, or cupola to the primary furnace and pour it on to Oxide of Iron and limestone on the hearth of the furnace. When working fluid iron there appears to be no difficulty in dephosphorising before decarburising, and the author is informed by Mr. George Hatton, of the Earl of Dudley's Steel Works, that, working with 2·0 per cent. Phosphorus pig, a metal with 0·10 per cent. Phosphorus and 2 per cent. Carbon can readily be obtained in the primary furnace for transference to the finishing furnace. If this can be done regularly it is a most important point, as nothing is of greater importance in basic Siemens work than the removal of Phosphorus before the Carbon. When a metal with 2·0 per cent. Carbon and 0·10 per cent. Phosphorus is transferred to the finishing furnace, the final steel must of necessity be very low in Phosphorus, as it is equivalent to working a hematite pig-iron, and the author is informed that at Kladno they are regularly producing steel with ·02 per cent. or less of Phosphorus in this way. To ensure this dephosphorisation, combined with rapid work, a very shallow bath of metal, about 6 to 8 inches deep, is necessary, and consequently very large

* *Iron and Steel Inst. Journ.*, 1897, vol. i., pp. 122 and 123.

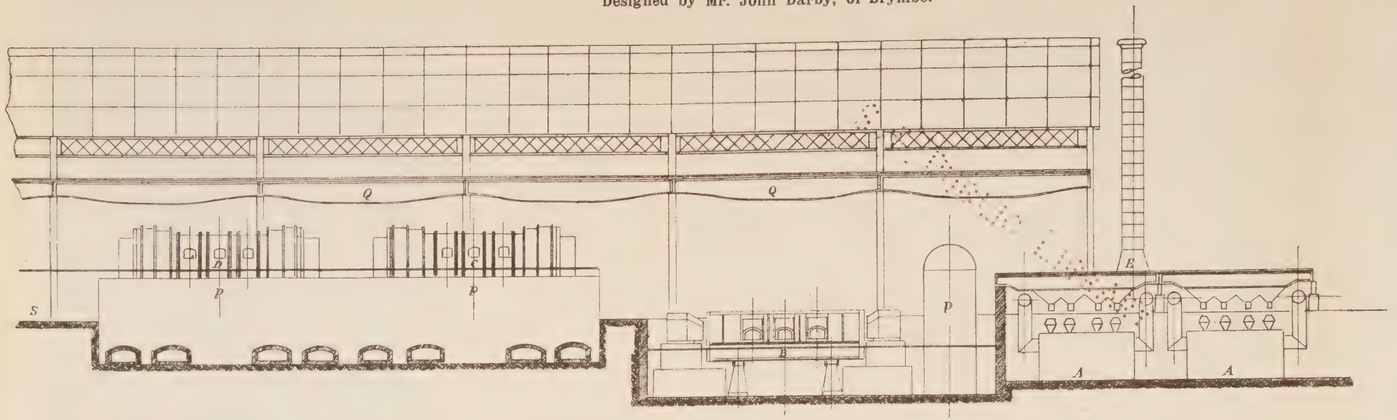
[To face page 198.

PLATE XII.—General Arrangement for the Bertrand-Thiel Process.

Designed by Mr. John Darby, of Brymbo.

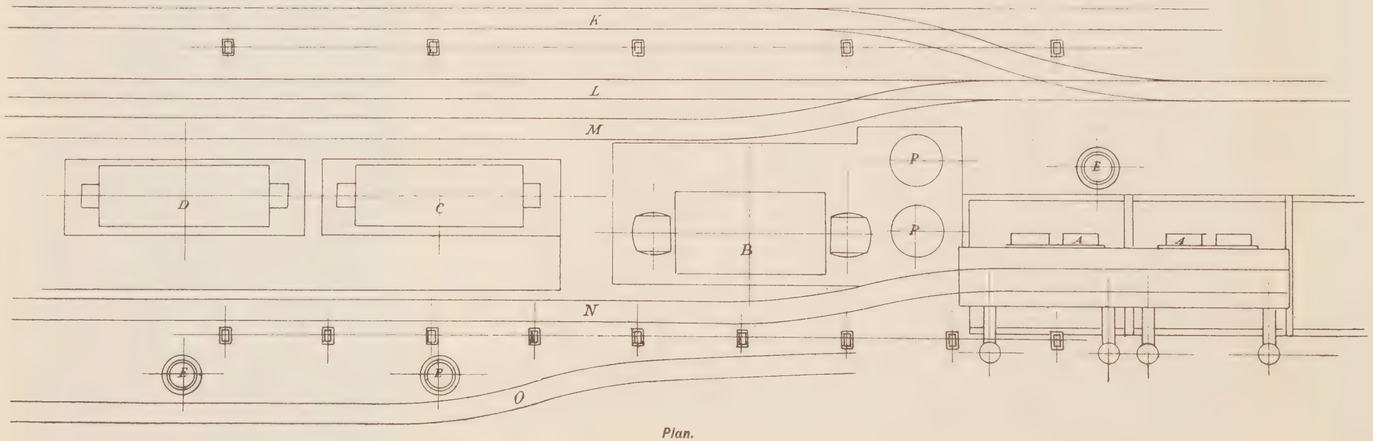
Blast-furnace metal is poured into the metal mixer, B, by means of a ladle. The mixer is gas fired, and has air regenerators, so that "week end" pig-iron and scrap can be melted if desired, but no attempt is made to dephosphorise, and neither ore nor lime or limestone is added. The molten metal is transferred from this mixer to the primary furnace, C, by the overhead travelling crane, R, and the ladle, F, and when the furnace is sufficiently full, iron ore and limestone are added as rapidly as possible. Within a period of three hours the whole of the Silicon should be removed, and in case of the pig-iron containing about 1·5 per cent. to 2 per cent. Phosphorus, the Phosphorus reduced to 0·15 per cent., while the Carbon, if the temperature has been carefully controlled, should not be less than about 2·00 per cent. The whole charge is now poured into a ladle, preferably with a large stopper and nozzle, and transferred by the overhead travelling crane, R, to the secondary furnace, D, which may contain highly-heated scrap ore and lime. Iron ore and limestone are added from time to time, and the metal "boiled down" to remove the last traces of Phosphorus, and to reduce the Carbon to the required extent. When finished, the whole charge is poured into the casting ladle, G, and teemed into ingot moulds. It is estimated by Mr. Darby that the time required for each charge in the finishing furnace will be under three hours, and, allowing for repairs between heats, that a pair of furnaces will produce eight charges in the twenty-four hours.

A, Gas producers.
B, Metal mixer.
C, Primary furnace.
D, Secondary or finishing furnace.
E, Chimney.
F, Transfer hot metal ladle from mixer to primary furnace.
G, Casting ladle.
H, Slag pot.
J, Ingot mould on car.
K, Through road.
L, Casting road.
M, Slag road.
N, Road to producers.
O, Hot metal road.
P, Regenerators.
Q, Crane runway.
R, Overhead crane.
S, Other furnaces as required.



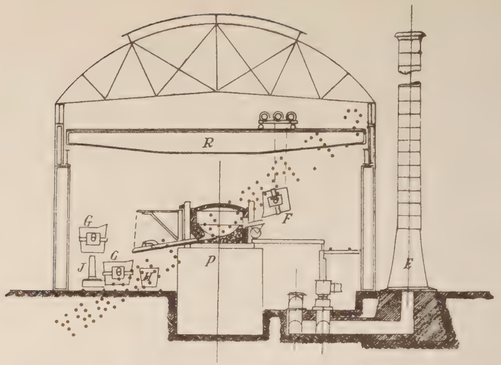
Elevation.

Fig. 165.



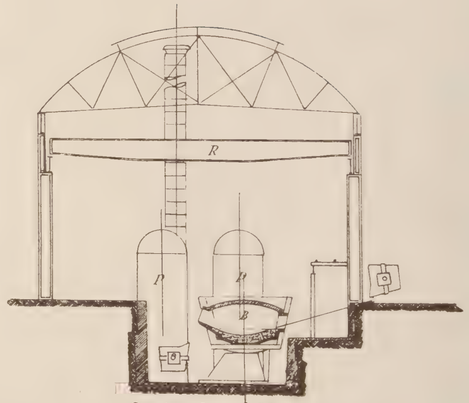
Plan.

Fig. 168.



Section through Melting Shop.

Fig. 166.



Section through Mixer.

Fig. 167.

furnaces must be used, far larger than the ordinary basic furnaces for the same weight of metal. The wear and tear on the furnace bottoms will in all probability be very considerable when using metal of the composition obtainable in England, as the fusion of Oxides on the furnace hearth cannot fail to soften it very much, and, when the molten metal is teemed into it, it is practically certain to cut it up. At Kladno they have an exceptionally good pig-iron, low in Silicon, and the bottoms are stated to stand remarkably well. Pig-iron of almost any description can be used in the Bertrand process, but it should be low in Sulphur and Silicon to obtain the best results as regards quality, and to keep repairs to the furnace within reasonable limits. The advantages claimed by the patentees for this process are—(1) High yield, 101 to 103 tons of ingots from 100 tons of metal charged; (2) a rich Phosphoric slag from the primary furnace, containing as much as 25 per cent. of Phosphoric acid; (3) increased speed of working; (4) low cost of plant, taking output into consideration; (5) low labour costs where fluid metal is used as in plant shown in sketch; and (6) superior quality of product.

There is no doubt that the yield is considerably higher than the ordinary Siemens, 101 tons having been obtained in actual working at Kladno. From Phosphoric iron a very rich Phosphoric slag can be obtained, as the great bulk of the Phosphorus present is concentrated in the slag from the primary furnace. So far no plant has been erected with large furnaces capable of holding 50 tons of metal, so that it is difficult to form an estimate as to what will be the speed of working in a large furnace of 50 tons' capacity or more. From the surface area of the Kladno furnace it appears that an ordinary Siemens furnace of 50 tons' capacity will not hold more than 25 tons of metal when working the Bertrand process, so that, although the speed of working is undoubtedly greatly increased, the quantity of metal turned out for the *same number of charges* will be only half that obtained from an ordinary Siemens furnace of same surface area, and hence the 50 per cent. greater output claimed by the patentees would necessitate very rapid working indeed. A great deal of confusion has been caused on this question of output, by speaking of a 50-ton furnace as a furnace which will hold 50 tons of metal, as what may be a 50-ton furnace, working the Bertrand, would be large enough to hold 80 to 100 tons under ordinary conditions of Siemens work, and consequently one may be comparing the output of furnaces of totally different capacity. This question of size of furnace within reasonable working limits is, however, only a matter of first cost. It is impossible to form a fair estimate as to the cost of plant and labour per ton of steel until the process is actually in operation upon a large scale, with a modern plant especially designed to insure large output; the plant at Earl Dudley's Steel Works has been partially altered to work this process, and several furnaces have been working for the last three or four years apparently with satisfactory results.

What is to all intents and purposes metallurgically the Bertrand-Thiel process is at work in the Hoesch Works in Germany. There are six 30-ton furnaces supplied with molten metal from a mixer; considerable quantities of Oxides and lime are charged on the furnace bottom, and then the molten metal is charged, the temperature being kept as low as possible to insure dephosphorisation before decarburisation. When largely dephosphorised the refined metal is tapped into a ladle, the Phosphoric slag separated, and the refined metal returned to the same furnace to be decarburised and converted into finished steel. The process is thus worked in two stages identical

with those of Bertrand-Thiel, and the only modification is that both stages are carried on in one furnace instead of two.

As regards the quality, there can be no question that both in respect to freedom from Phosphorus and other impurities, and as regards mechanical properties, steel of the best description can be produced by this process.

Figs. 165 to 168 represent a plant designed by Mr. John Henry Darby, of Brymbo, for working the process on a large scale, which he has kindly allowed the author to reproduce.

The Talbot Continuous Process.—Practically all the processes that have been introduced to increase the output and improve the yield of the basic open hearth process have depended upon the use of fluid metal, with large additions of Oxides, and the difficulty has always been to prevent the destruction of the hearth by the combined chemical action of the Oxides and the mechanical abrasion of the fluid metal when poured into the furnace.

This problem of the treatment of fluid pig-iron of more or less irregular composition, as regards Silicon or Phosphorus, has been most effectively attacked by Mr. Benjamin Talbot, formerly of Pencoyd, in what is known as the continuous open hearth process. In this process a basic-lined tilting furnace is used, especially designed so that any quantity of slag and metal can be poured off at any time during the working of the charge, and also that large or small additions of oxidising agents, limestone, or metal can be added. The process of working is as follows :—

On Saturday, after completely or partially emptying the furnace, gas is taken off for a short time, whilst the gas tubes are cleaned. This now only takes an hour or two, when gas is again put on, and the furnace slowly filled up during Saturday night and Sunday with molten pig-iron from the blast furnace, or partly from blast furnace and mixer. On Sunday evening when the ordinary shift comes out the furnace is usually practically ready for tapping. Assuming the furnace to be just tapped, it is turned back and a pan of slag taken off, and any necessary repairs made round the slag line on the far bank. Lime, scale, or iron ore are then added in the requisite quantity, the front banks and jambs round the doors are then fettled, and the molten pig-iron from the blast furnace, or preferably the mixer, poured in. This is usually brought up in two ladles of, say, 25 tons each, assuming the amount tapped to be 50 tons, which is the usual amount cast. As a rule, very little reaction occurs, as it is found best to avoid anything approaching a violent reaction, so that all the pig-iron can be added at once, and less time appears to be lost in charging the metal and preparing the slag. The charge soon picks up heat, and comes on the boil, reacting with the oxide, and lime is rapidly absorbed by the slag. The slag gradually thickens, but rarely foams up unless the Silicon is high in the pig-iron charged. It is "opened out" with a small quantity of scale or iron ore, and soon boils clear, within about an hour or an hour and a-half of charging the molten metal. The boil continues without further additions for two or three hours, until the Carbon is boiled down to about 0·25 per cent. A pan of slag is then drawn off, and a further amount of scale and lime added, in order to make the finishing slag and to work the charge down to the requisite Carbon. A little pig-iron is often added to pig back and get an ingot free from any tendency to pipe. When the pig-iron contains sufficient Phosphorus, the basic slag is sold as a manure. The old trouble in working basic charges of having Phosphorus left in the bath when the Carbon has all gone is practically unknown, provided the Phosphorus does not exceed 1·75 per cent., as under the above conditions Phosphorus is largely eliminated before the Carbon.

By the device of keeping the furnace hearth always two-thirds full of molten metal, the fluxing action of the slag on the basic lining is confined to a few inches above the bath of metal on which it floats, as it never comes near the bottom of the furnace, except when the furnace is being emptied at the end of the week. Thus, a slag which, in the ordinary method of working the Siemens process, would almost destroy the bottom of a basic furnace, has no appreciably destructive effect on the lining when the furnace hearth is protected by a bath of molten metal. When working the furnace very hot, as with low Phosphorous irons, the reaction between the Carbon and Oxides is so vigorous that the combustion of the **CO** given off is sufficient to maintain the heat of the furnace during the reaction when all the gas is shut off from the producer, although in practice it is not usual to work the furnaces so hot as this. When working at a lower temperature to dephosphorise before decarburising, this reaction is slower, and the sudden generation of **CO** filling the entire furnace with flame does not take place to the same extent. The rapidity of working depends upon the temperature, the composition of the pig-metal introduced, and the percentages of metal removed and charged each time; the purer and hotter the molten-pig metal and the smaller the charges, the more rapid the purification. Thus, when charges equal to one-third of the total capacity of the furnace, with 1·0 per cent. of Phosphorus and ·5 per Silicon are worked, each heat is finished in from four and a half to five hours, and about four heats are made in the twenty-four hours, whereas when working charges equal to one-tenth the total charge the purification is effected in about one hour, The usual practice, however, is to work with a charge equal to about one-third of the total capacity of the furnace.

To obtain the very best results, experience has shown that, as in the case of the basic open hearth furnace using molten metal, the blast furnace metal should be first passed through an active gas-fired mixer, where it is largely desiliconised and desulphurised, and a hot metal, regular in composition and low in Silicon, produced.

The time required for working charges will vary with the composition of the pig-iron, the size of the furnace, etc. With Cleveland iron in a 175-ton furnace the time from tap to tap will be from 5½ to 6 hours, and the output per week will be from 1,100 to 1,300 tons, with a yield of 103 to 104 tons for each 100 tons of pig-iron charged; the same size of furnace working with hematite pig-iron direct from the blast furnace will produce 1,200 to 1,400 tons of ingots per week, with a yield of 105 to 106 tons of ingots per 100 tons of pig-iron charged. With desiliconised mixer metal the output with hematite iron would probably be considerably increased, although the yield might be reduced. The rapid elimination of impurities is due to two causes—(1) Rapid oxidation by the molten metal being poured through a layer of molten fluid basic slag rich in oxides of iron, by which means slag and metal are brought into very intimate contact, thus insuring the essential and best conditions for rapid chemical action. (2) Dilution by mixture of the partially purified mixer metal with three or four times its weight of finished steel.

The rapidity of working will largely depend upon the percentage of Silicon and Phosphorus in the metal, and, other things being equal, the lower the Silicon the more rapid the work. The condition of the Carbon in the molten metal also seems to have a most important influence on rapidity of working, as metal, in which graphitic Carbon readily separates in the ladle, works much more slowly than metal in which it remains combined with the iron.

An important point in the Talbot process, from a practical point of view, is the readiness with which a regular supply of ingots can be supplied to the mills at frequent intervals, and in any required quantity, the ingots being taken direct from the casting pit to mill furnaces. It frequently happens in ordinary Siemens practice in large works, where a number of furnaces are working, that three or four will be ready to tap at or about the same time, with the result that far more ingots are produced than the mill furnaces can deal with at once, and consequently a number have to be allowed to cool down, and be re-heated at extra cost, or, on the other hand, mills may have to wait for the Siemens furnace. This can be, to a great extent, obviated in working on the Talbot system, as the time of tapping of the metal can be better controlled to suit the requirements of the mills.

Furnaces up to 250 tons are now working in America and England, but it remans to be seen if this is a more economical unit than the 175 or 200-ton furnace when against increased output is set the extra capital expenditure, cost of repairs, etc. The 250-ton furnace working in England has been in operation for a few months only, and the time is too short to form an opinion as to its advantages or disadvantages compared with the somewhat smaller furnaces.

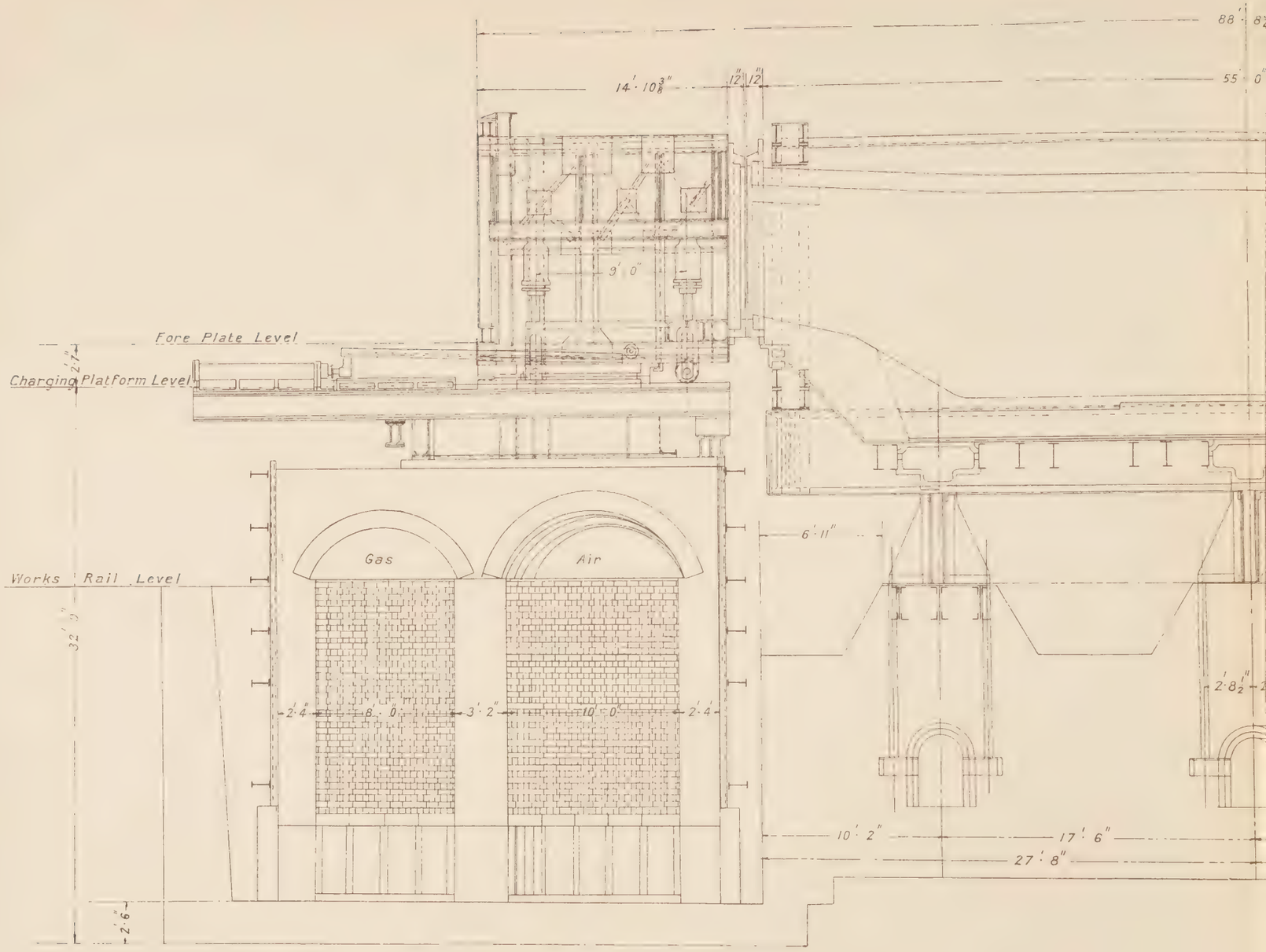
This process has made considerable progress during the last few years, some 11 or 12 furnaces now being in regular work in England at five or six different works, while in America Messrs. Jones & Laughlins have had nine 200 to 250-ton furnaces in operation for the last three or four years, and are putting down at their new works at Aliquippa furnaces of 275 to 300 tons capacity. At Witkowitz, in Austria, four large furnaces are now in course of erection. The total output in Europe and America for the last year was approximately 1,000,000 tons, and when the furnaces now under construction in America are in operation, this will be largely increased.

In the design of the furnaces themselves considerable improvements have been made since the original furnace was started at Frodingham. In the United States central rotation of the furnace, as distinct from the rolling-forward movement, has been commonly in use. This method of rotation has now been successfully employed at the Skinningrove Works, where the latest furnace has been put up. The advantage of this is that the gas can be kept on the furnace during the whole time of tapping, whereas in those furnaces which roll forward on the Wellman system, gas has to be taken off the furnace during tapping.

Another improvement which has added very largely to the length of time these furnaces can run without being put off for repairs, is the complete separation of the block from the tilting portion of the furnace, which was always a source of weakness, owing to excessive wear. The gas and air are now brought up in flues in the movable port end, and given the necessary direction in this part of the furnace. The air enters over the gas in one opening. The arch between the gas and air is protected by three or four iron water-cooled pipes, through which water constantly circulates. These tubes are practically exposed to the direct flame, and, so long as the water flows rapidly through them, there is little tendency for them to burn. On the movable port end a water-cooled chill encircles the air and gas ports, a similar chill is on the tilting section, but this has one central opening only, and thus the old form of block in the furnace is completely done away with. This furnace is shown in fig. 169, Plate xii*a*, and should be compared with the ordinary Wellman furnace described on page 149 (fig. 133), and also figs. 170, 171, and 175 (Plates xiii. and xiv.). Figs. 174 and 175 (Plate xiv.)

This furnace is very similar to the ordinary Wellman type, the principal difference being in a greater depth in the body and the details of the construction of the "block," which is quite separate from the tilting section and can be run back from furnace and rapidly cooled for repairs. In the tilting section there is only one opening at each end, the separate gas and air passages being entirely in the movable port ends. Before tilting the "block" is moved a few inches from the furnace by the hydraulic cylinder shown; there is no water seal over the passages from the regenerators to the ports, and the joint between the port and the furnace is made by water-cooled chills.

PLATE XIIa.—250-Ton Talbot Furnace.



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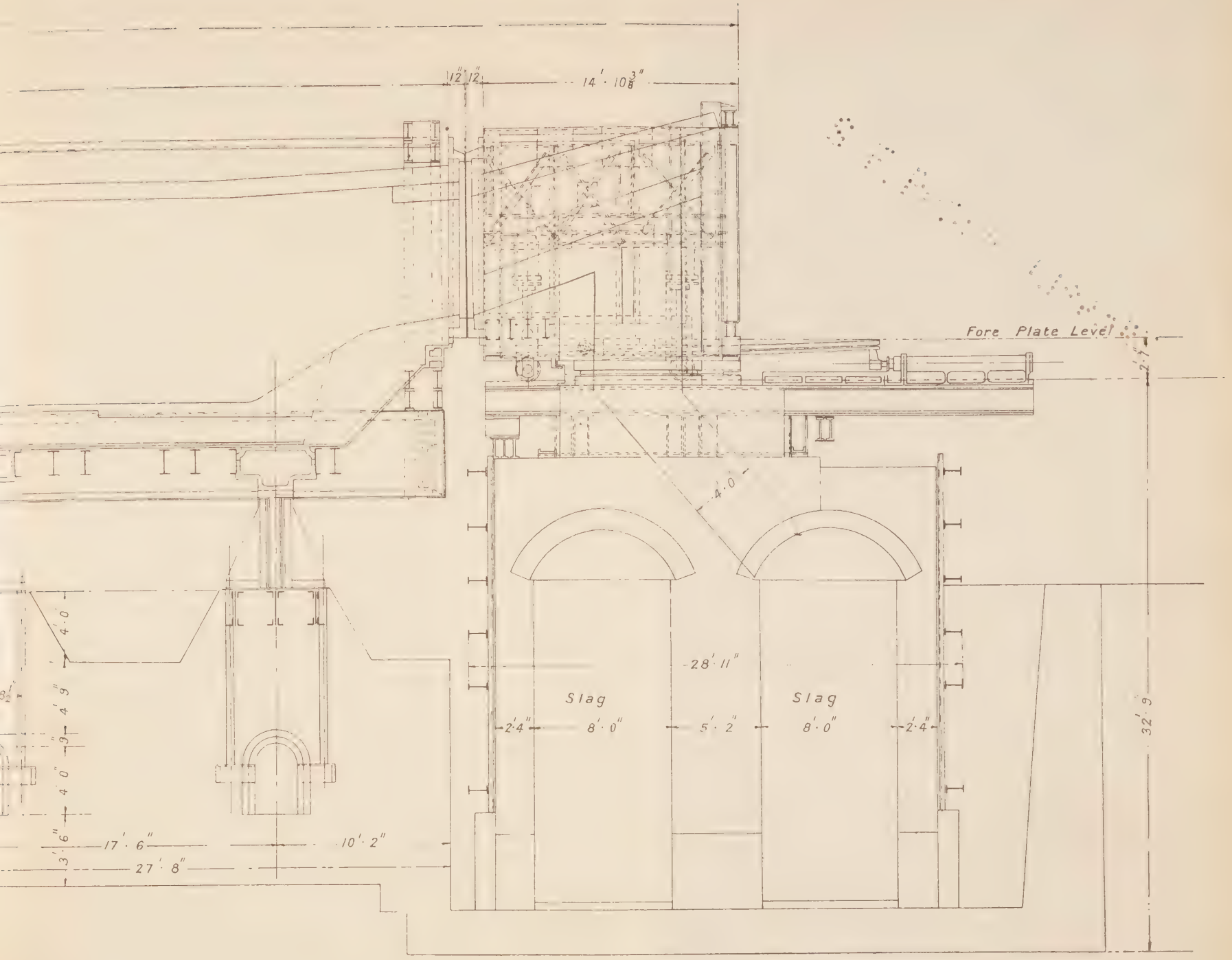


ig. 169.

PLATE XIII.—Tilting Furnace, adapted for Talbot Process.

[To face page 202.

This furnace is very similar to the ordinary Wellman type, the principal difference being in a greater depth in the body of the furnace, and in details of the construction of the port, which is designed so it can be run back from the furnace to enable a man to get between it and the furnace for repairs. The port is moved a few inches from the furnace, before pouring, by a hydraulic cylinder to allow the furnace to tilt freely, but there is no water seal over the passages from the regenerators to the ports, the joint being made by hollow steel water-cooled chills. A slag hole is provided at the charging side, so that slag can be poured off from either side of the furnace. The joint between the port and the furnace is made by water-cooled chills.

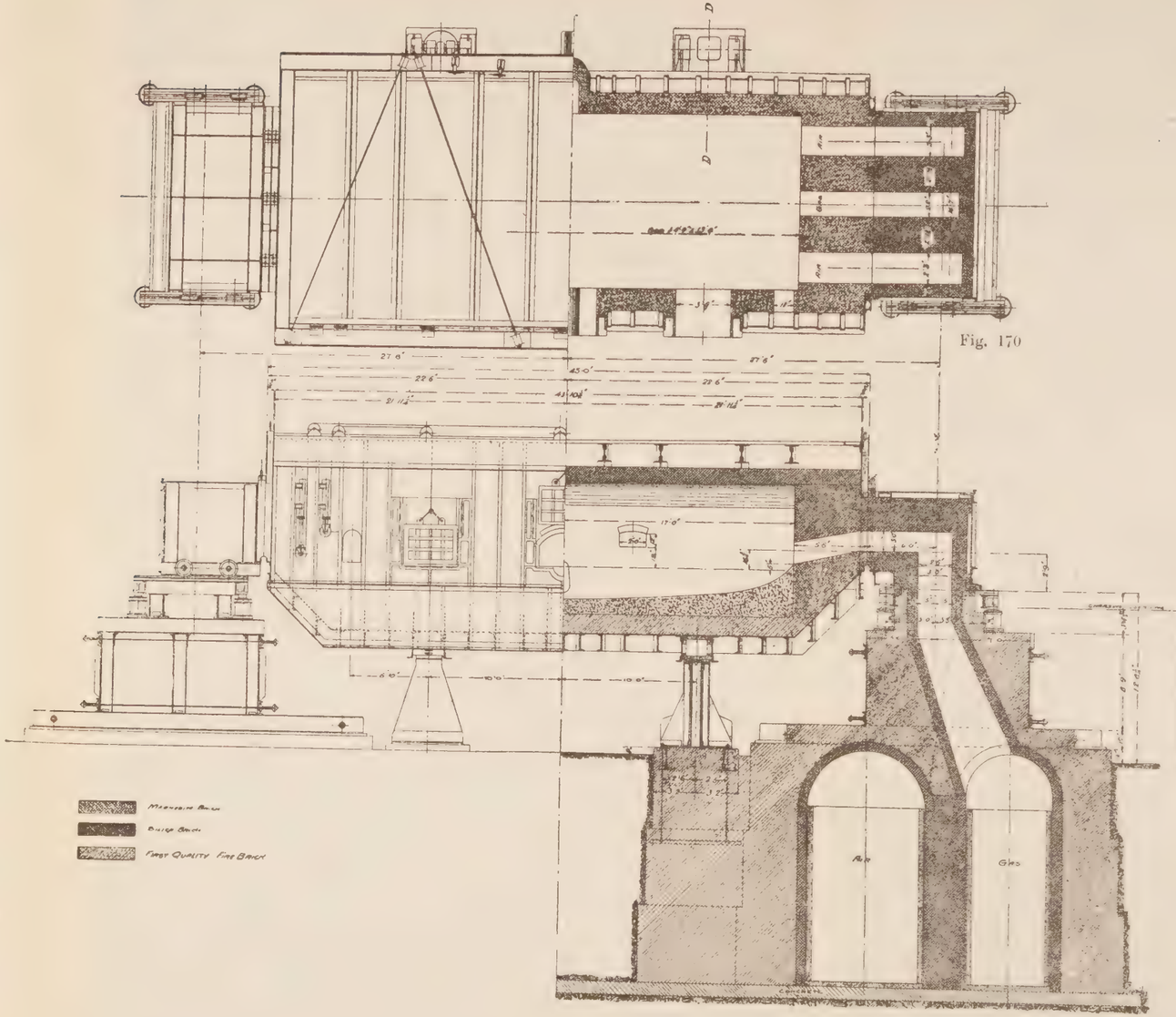


Fig. 171.

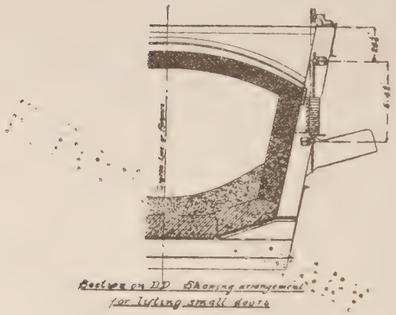


Fig. 172.

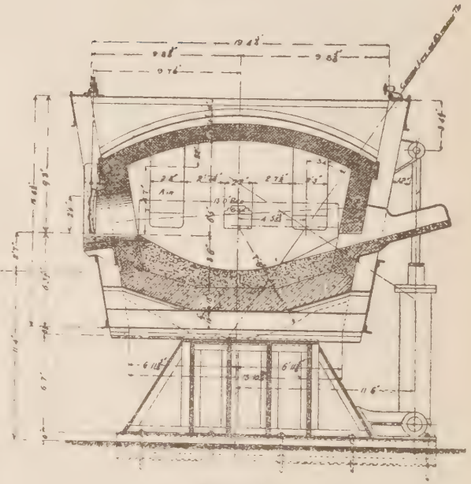


Fig. 173.

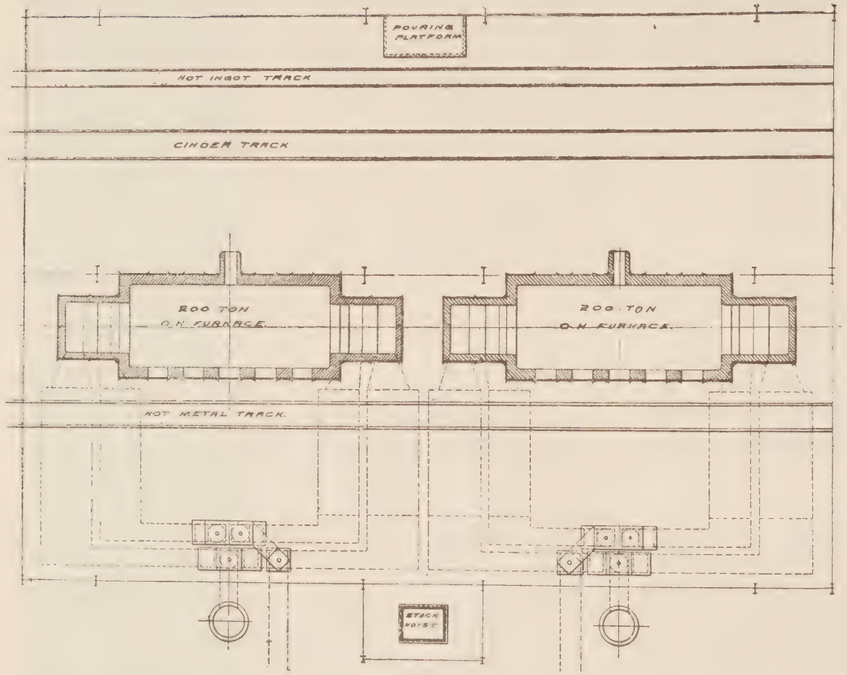
Fig. 170

PLATE XIV.—Talbot 200-Ton Plant.

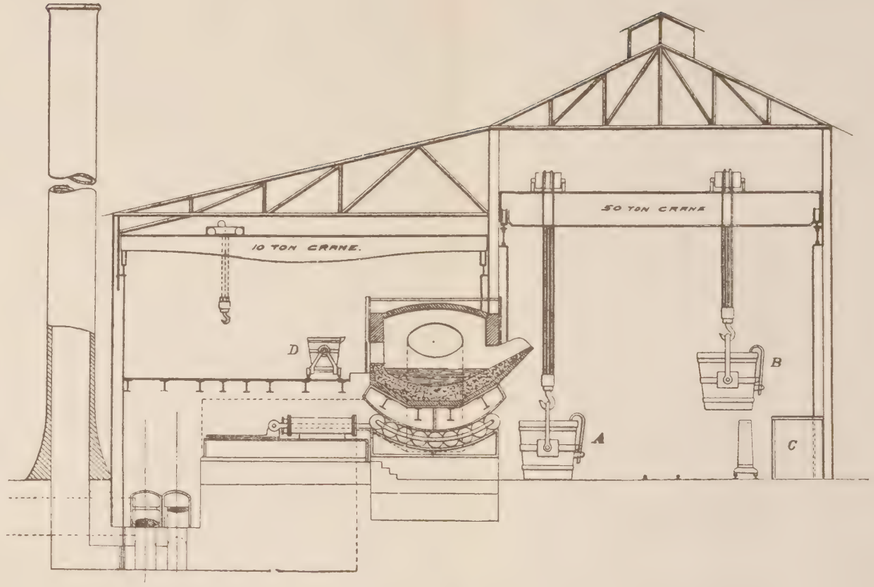
[*To face page 202.*

Showing method of filling the furnace and pouring and teeming the finished steel into ingot moulds on cars.

A, Ladle ready to receive finished steel.
B, Ladle ready for teeming the ingots.
C, Tapping or pouring platform.
D, Hot metal ladle ready to pour metal into furnace.



Plan.
Fig. 174.



End View.
Fig. 175.

show plan and sectional view of Talbot plant with central rotating furnaces of the Talbot type.

In the new plant at Witkowitz, Austria, which is now in course of erection, there will be four large tilting furnaces for the Talbot process, which will follow largely the lines of the Skinningrove furnace, but which will be arranged to be electrically tilted, as most of the furnaces in America are, whereas in Great Britain all the furnaces are tilted by hydraulic power.

As regards the quality of steel produced when working hematite iron, the product is exceptionally pure, and when the usual basic pig-iron with, say, 1·7 per cent. of Phosphorus is used steel is obtained in every respect equal to basic Siemens from the same class of pig-iron. The removal of Sulphur and Phosphorus takes place under conditions similar to those in the ordinary basic Siemens, the Talbot process having the advantage that the temperature of the bath and the composition of the slag can be more readily controlled and modified to suit the conditions of working.

The great possibility of the Talbot process, however, in the opinion of the author, lies in the facilities it offers for extremely rapid work with ordinary hematite iron as at present used in Siemens and Bessemer acid practice. In working metal of this kind, especially if it is first passed through a mixer to insure fairly average composition, the output should be very large indeed, as the Silicon, under basic conditions of work, is oxidised almost immediately, and it only remains to reduce the Carbon to the required extent, which can be done very rapidly, and the steel is ready to teem into the ingot moulds.

The Twynam Process.—A process of direct reduction of iron ore to steel has been patented by Mr. Twynam in several countries. In some early experiments carried out at Brymbo some years back, Mr. Twynam found that the reduction of iron, from iron ore and Carbon briquettes, thrown into the bath of metal in a basic-lined open hearth furnace, was very rapid and complete: thus in one experiment, in which 30 cwts. of such briquettes were added, the slag, ten minutes after the last of the briquettes had been thrown in, contained only 1·08 per cent. **Fe**, with 19·3 per cent. Phosphoric acid. The comparatively small quantity of such briquettes which can be added to a charge in a fixed furnace and the growth of the banks and bottoms which was found to result, caused the abandonment of the experiments. These difficulties would appear to be overcome by effecting the direct reduction of a mixture of ore or Oxide and Carbon (preferably briquetted), in conjunction with the continuous working of a basic-lined open hearth furnace, preferably of large dimensions and of the tipping type, such as those now used for the Talbot process. The addition of such briquettes would be made continuously throughout the week, the excess of slag would be poured off from one side of the furnace, and the metal, either as finished steel, or metal for further treatment in a second furnace, would be teemed from time to time as the capacity of the furnace demanded. There should be no trouble with the bottom or side growing, as there is with a fixed furnace worked in the ordinary discontinuous way, as the large reservoir of metal always present in the continuous method of working, would, it is claimed, wholly prevent this.

The Monell Process.—In this process, instead of charging iron ore, limestone, and cold pig-iron, the ore and limestone are first charged, heated to a high temperature near to insipient fusion, and then molten iron poured into the furnace. The process is described as follows, by Mr. Monell*:—

* *Iron and Steel Inst. Journ.*, 1900, vol. i., p. 75.

"The process consists in charging in a basic open hearth furnace limestone and a relatively large quantity of ore, heating these, and then charging molten pig metal taken from a mixer or direct from the blast furnace. The temperature of the resulting mixture must be sufficiently high to produce a rapid slag formation, and yet low enough to ensure the rapid oxidation of the Phosphorus. The slag formed rises in a foam and is drawn off at a cinder notch. One hour after charging the molten pig the bath is practically free from Phosphorus, Silicon, and Manganese, and the bulk of the slag containing the impurities has been removed. The bath is then in the best possible condition to be acted on by the flame and remaining ore which has not yet been reduced. The steel may be tapped when the Carbon has reached the desired point. Either mill scale or tap cinder may be substituted for the ore, and the proportion of Oxide may be varied according to the percentage of Carbon desired in the finished product."

The only difference between this and the ordinary basic Siemens process consists in preheating the limestone and relatively large quantities of ore in the furnace, charging molten metal instead of cold pig-iron, and removing the bulk of the slag through a cinder notch at an early period of the working of the charge. The process is stated to have given good results at the Homestead Works; it has been tried experimentally at one works in England, but the results were not sufficiently promising to lead to the process being adopted.

There is no doubt that any process which brings highly heated Oxides under basic conditions into intimate contact with fluid iron, will lead to rapid purification of the iron, but the semi-fusion of Oxides on a basic hearth must inevitably soften the bottom of the furnace, entail very heavy repairs, and generally cause considerable trouble in working, especially when dealing with Phosphoric and more or less silicious irons, such as are usually used in this country. Further, the removal of the slag at an early stage of the operation must inevitably lead to considerable waste of Oxide of Iron, as the slag at this period must of necessity contain a very high percentage of iron.

Duplex Process.—Various attempts have been made at different works to combine the Bessemer and basic open hearth processes by partially blowing the metal in an acid or basic converter and then finishing in the basic open hearth, but, so far, they have not been attended with great success. One of the latest developments in this direction is to desiliconise in an active mixer, blow down in basic converter, to remove the greater part of the Phosphorus, and then finish in a basic open hearth, using about two-thirds blown metal and one-third molten mixer metal for the open hearth charge. By this means the output of the open hearth plant has been more than doubled, and the gain in this direction is so great that it alone seems almost to justify its adoption. Important, however, as output is, it is not everything, and the costs of Bessemerising, together with the decrease in yield, are very serious drawbacks, and it is doubtful if the advantages are not more apparent than real. Under special circumstances, where pig-iron is very cheap, fuel dear, and labour costs high it might pay to waste a considerable percentage of iron in return for a great increase of output, but even under these conditions most careful investigations would be necessary before a definite opinion as to the economy of this method of working could be given. Although in some special cases a modification of the duplex process may be found to be economical, the fact remains that in most cases the extra costs of working two processes, and the low yield of ingots, has been found as the result of

experience, to more than counterbalance any gain due to the increase in output, &c. At present the use of molten mixer metal, refined as far as possible in an active mixer, so that Silicon is reduced to 0·5 per cent. or less, and taken direct to an open hearth Talbot or similar furnace, must be considered the most economic method of working.

Heat Developed by Oxidation of Metalloids in Siemens and Allied Processes.—It has already been mentioned in Chapter v., when considering the thermo-chemistry of the Bessemer process, that the heat units evolved by the oxidation of the impurities in the open hearth process are the same as in the Bessemer, less the heat absorbed in the reduction of the Oxide of Iron to supply the necessary Oxygen. In the ordinary acid process, when the pig-iron and scrap are charged cold, about 40 per cent. of the impurities present are oxidised by the flame during melting, and consequently it is only the metalloids remaining in the metal when melted which are oxidised by the Oxygen from the ore added. In the basic Siemens, when Oxides are added with the cold charge, these react during the melting period, and it is impossible to say how much oxidation is due to these, and how much to the direct action of the flame. We shall, therefore, consider the case where the metal is charged into the furnace in the molten state.

Assuming that *molten pig*-iron and *fluid Oxides* are brought together at such a temperature that they can react, the net result of the oxidation of the Silicon to SiO_2, of Phosphorus to P_2O_5, and of Manganese to MnO, after allowing for heat absorbed by the reduction of the Oxide of Iron, is a gain, and the net result of the oxidation of Carbon to CO by Oxide of Iron is a loss.

If all the Oxide is added in the form of Fe_2O_3, some will be reduced to FeO, will unite with the Silica to form a slag, and some will be reduced to Fe. If a mixture of FeO and Fe_2O_3, such as Oxide cinder, roll scale, &c., is added, as is a common practice in basic Siemens working, there will be sufficient FeO to unite with the Silica, and no heat units will be necessary for its reduction. The Carbon is oxidised by the Oxide to CO, and this CO, as it escapes from the bath of metal, is burnt to CO_2 by the Oxygen in the gases with a further development of heat; but, in the ordinary process, this evolution of CO is very gradual, is spread over a long period, and it is not fair to assume that the heat is effective to any appreciable extent.

In the Talbot process the total heat units developed and absorbed are exactly the same as in the case of basic open hearth working with molten metal, but it is claimed that, although the heat developed is the same, it is *practically much more effective*, as the greater portion of the Silicon and Carbon is removed, during the first half hour, after charging the molten metal, and the heat units are concentrated in the bath; the loss by radiation is thus far less than if the reactions were spread over some hours, as in the ordinary Siemens. Again, although the Carbon, oxidised to CO in the bath, is attended with absorption of heat, the CO is evolved in such quantities that in burning to CO_2 it fills the entire furnace with flame, and during the reaction the gas is shut off from the furnace, the heat developed by the combustion of the evolved CO being sufficient to maintain the heat of the bath. It therefore seems reasonable to admit that both the rapid oxidation of the Silicon and the combustion of the CO to CO_2 by the hot air from the regenerators is attended with an effective gain in heat units.

The Talbot and the ordinary open hearth process may be compared respectively with two converters, one with an ample supply of air so that the oxidation of the impurities is completed in a short time, and one with a

deficient supply of air, in which the oxidation of the same quantities of impurities takes three or four times as long. In both cases the total heat evolved is the same, but the temperature of the baths of metal at the end of the operation will be very different.

The heat units evolved in the Bertrand-Thiel process, for the same composition of metal, will be the same as in the basic Siemens.

As an example for calculating the heat developed by the oxidation of the impurities, we will take 1000 kilos. of metal, of the following composition:—Carbon, 3·5 per cent.; Silicon, 1·0 per cent.; Phosphorus, 1·0 per cent.; Manganese, 1·5 per cent.

The following figures will be required for the calculations:—

HEAT DEVELOPED BY COMBUSTION OF 1 KILOGRAM OF ELEMENT.

C to CO_2,	8,080	heat units or calories.
C ,, CO,	2,450	,,
Si ,, SiO_2,	6,414	,,
P ,, P_2O_5,	5,890	,,
Mn ,, MnO,	1,654	,,
Fe ,, FeO,	1,232	,,
Fe ,, Fe_2O_3,	1,746	,,

There are 700 grammes of Fe in every kilo. of Fe_2O_3, therefore the heat absorbed by the reduction of 1 kilo. of Fe_2O_3 will be—

$$\frac{1{,}746 \times 700}{100} = 1{,}222{\cdot}2 \text{ heat units.}$$

1,000 kilos. of metal of above composition will contain 35 kilos. of Carbon, 10 kilos. of Silicon, 10 kilos. of Phosphorus, and 15 kilos. of Manganese.

It is assumed that FeO is added in sufficient quantity to combine with the SiO_2, and no allowance is made for the reduction of the Fe_2O_3 found as FeO in the slag, it being assumed that the whole of Fe_2O_3 is reduced to metallic iron. As a matter of fact, this assumption does not appreciably affect the result, and only makes a difference of about 200 heat units. No allowance is made for the heat developed by the combination of SiO_2 and P_2O_5 with the bases in the slag, as the heat of formation of these is somewhat doubtful; on the other hand, no correction is made for the heat absorbed in the dissociation of the Silicides and Phosphides in the metal, but these may be fairly considered as balancing each other, and, if anything, probably the heat developed is greater than that absorbed.

As the Silicon, Phosphorus, and Manganese show a nett gain in heat units, we will consider these first.

SILICON.

	Heat Units.
10 kilos. of Si evolve on oxidation,	$6{,}414 \times 10 = 64{,}140$
10 kilos. of Si require 38·1 kilos. Fe_2O_3, absorbing	$38{\cdot}1 \times 1222{\cdot}2 = 46{,}564$
Heat units evolved,	17,576

PHOSPHORUS.

	Heat Units.
10 kilos. of P evolve on oxidation,	$5{,}890 \times 10 = 58{,}900$
10 kilos. of P require 43·0 kilos. Fe_2O_3, absorbing	$43 \times 1222{\cdot}2 = 52{,}554$
Heat units evolved,	6,346

MANGANESE.

	Heat Units.
15 kilos Mn evolve on oxidation,	$1{,}654 \times 15 = 24{,}810$
15 kilos. Mn require 14·5 kilos. Fe_2O_3, absorbing	$14{\cdot}5 \times 1222{\cdot}2 = 17{,}722$
Heat units evolved,	7,088

We thus see that in each of the above cases more heat is evolved than is absorbed, and the total heat units evolved equal

$$17,576 + 6,346 + 7,088 = 31,010 \text{ heat units.}$$

On the other hand, if we consider Carbon, we have

	Heat Units.
35 kilos. **C** evolve on oxidation to **CO**, . . .	$35 \times 2,454 =$ 85,890
35 kilos. **C** require 155·7 kilos. Fe_2O_3, absorbing	$155{\cdot}7 \times 1,222 =$ 190,265
Heat units absorbed, ...	104,375

	Heat Units.
Thus by oxidation of Carbon we have an absorption of . . .	104,375
And by the oxidation of **Si**, **P**, and **Mn** an evolution of . . .	31,010
Showing a loss of	73,365

This is without making any allowance for heat units developed by the combustion of **CO** to CO_2 by the free Oxygen passing into the furnace, and if we take this we get

35 kilos. of **C** burnt from **CO** to CO_2 by Oxygen, $35 \times 5,630 = 197,050$ heat units evolved.

Assuming that all these heat units were utilised, the nett results would be—

	Heat Units.
Heat units generated by **Si**, **P**, and **Mn**, ...	31,010
Heat units generated by combustion of **CO** to CO_2, . . .	197,050
Total heat units evolved, ...	228,060
Less heat units absorbed by combustion of **C** to **CO** by means of Fe_2O_3,	104,375
Nett total of heat units generated, ...	123,685

Even in the Talbot process it is not reasonable to assume that all the heat generated by combustion of **CO** to CO_2 is effective, but if we assume that one-third is utilised in the furnace it will practically balance the loss entailed by the reduction of the Oxide necessary for the oxidation of Carbon to **CO**.

To sum up, we may say that **Si**, **P**, and **Mn** are heat producers in all open hearth processes, while the combustion of Carbon is attended with more or less loss of heat, varying with the conditions of working, so that the nett result is a loss, and extraneous heat has to be supplied not only to compensate for this, but to supply the heat necessary for fusing the Oxides and basic additions, and the heat lost by radiation, &c.

General Arrangement of Open Hearth Melting Shop.—The usual form of casting pit in a Siemens furnace plant is a long straight pit, about 6 feet deep, and running the entire length of the shop in front of the furnace, and in this the ingot moulds are placed. The casting ladle on a carriage (fig. 151, p. 165), is either run on rails over the pit, as shown in figs. 117 and 125, or suspended by an overhead crane capable of traversing the entire length of the shop. This arrangement of pit is still very common, but the tendency in modern works has been to move the casting pit further away from the furnaces when possible. The simplest way of doing this is to take the casting ladle away on a suitable railroad by means of a locomotive to a straight pit at a reasonable distance from the shop, or it may be taken away to a circular pit and the ladle transferred to a central casting crane. This last arrangement is in use in several works in England, and was formerly in use at the Homestead Works in America. Fig. 176 gives a general plan of the melting shop at the latter works in 1890, and shows the arrangement

for removing the ladle, when full of steel to the casting pit. This plant is a very costly one, as there are ten large hydraulic cranes to eight furnaces. By raising the furnaces in the ordinary way to such a height above the ground level that the casting ladle can be run under the spout of the furnace for tapping, all the central cranes in front of the furnaces are dispensed with, and only those in the casting pits are required.

Both at Pencoyd and at the Phœnix Iron Works in America a semicircular pit is arranged in front of each furnace, with one hydraulic top-supported crane serving each furnace, as shown in fig. 177. This is distinctly an expensive installation, but less so than the Homestead arrangement.

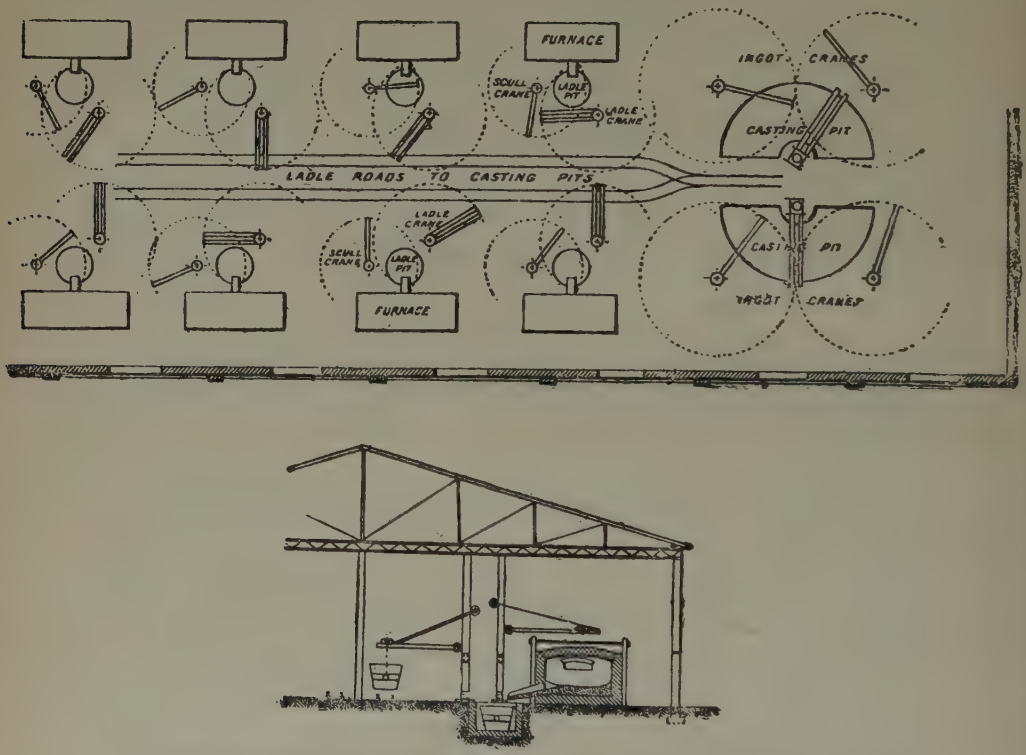


Fig. 176.—General Arrangement of the Homestead Siemens Melting Shop, 1890.

The furnaces stand in two rows, with two ladle roads between them. The furnaces, as shown in the sketch, are built so that the taphole is only just above the ground level, and the casting ladle is lowered into a pit in front to receive the charge of steel. In front of each is a 60 ton hydraulic ladle crane and a 5-ton slag and scull crane, both top-supported and built of H beams. After the metal is tapped into the ladle the latter is transferred to a four-wheeled bogie-car, run by a locomotive to one of the semicircular casting pits, where it is again transferred to one of the 60-ton central casting cranes and the metal teemed. There are two ingot cranes to each casting pit, as shown.

In view of the introduction of car-casting, the ladle suspended from an overhead crane running in front of the furnaces seems to be one of the best

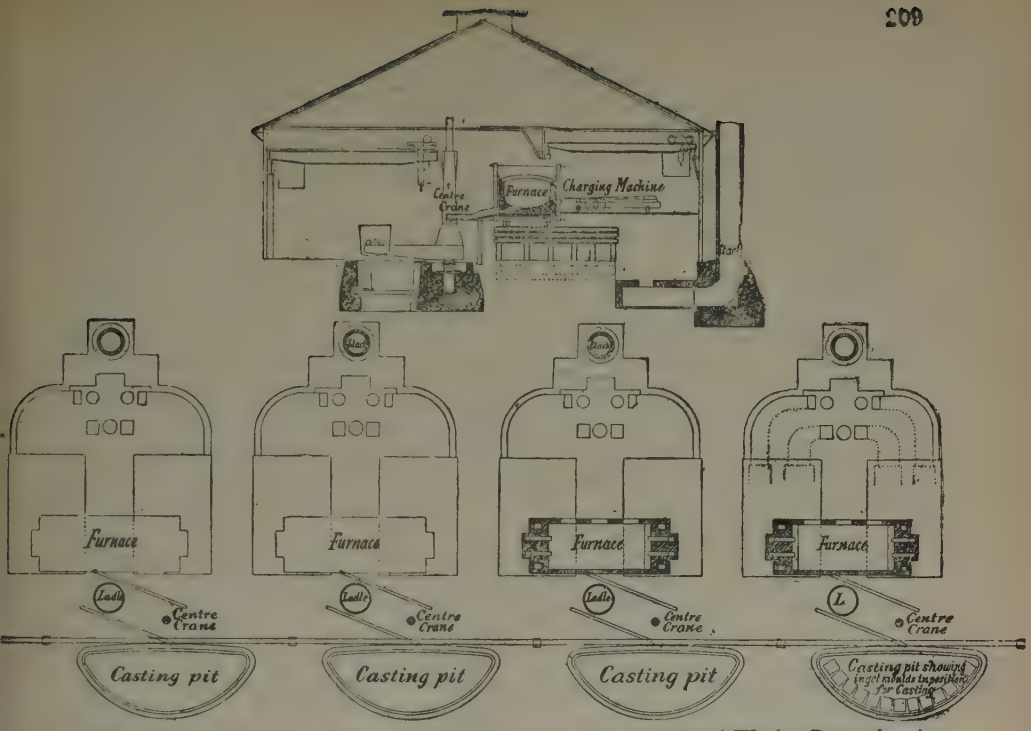


Fig. 177.—General Arrangement of Melting Shop at Pencoyd Steel Works, Pennsylvania.

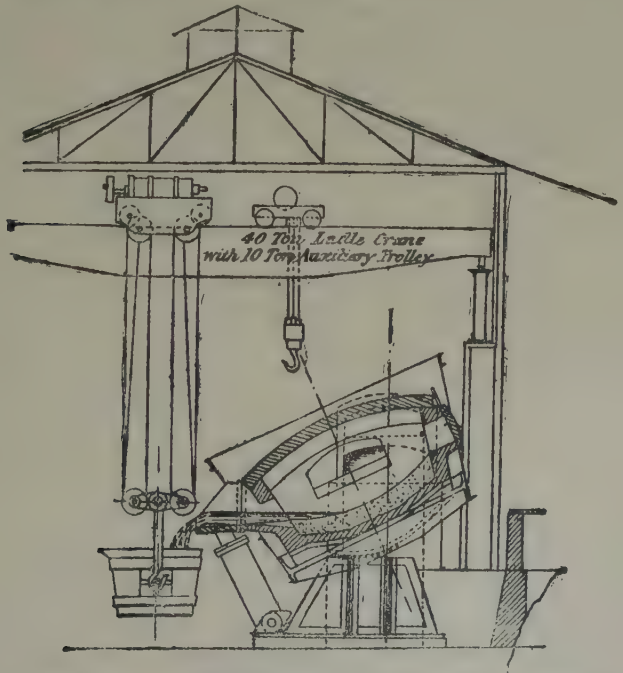


Fig. 178.—Wellman Furnace, with Casting Ladle carried on Overhead Ladle Crane.

arrangements, and is now largely used in America. The ladle can be readily raised or lowered, and, provided the span of the overhead crane is fairly large, the casting can be done a good distance in front of the furnace, and not necessarily right under its spout. Fig. 178 shows this method of casting as applied to a Wellman furnace. With a good type of modern crane, similar to that shown in fig. 153, Plate xi., the ladle can be easily manipulated, and it is probably the best system, especially when casting on cars is adopted.

Another modification in casting was some years ago introduced by Mr. Wellman, who, by means of an attachment to the front of the furnace known as the fore-hearth, dispensed with the casting ladle altogether. It really consisted of a ladle fixed on to the front of the furnace provided with two ordinary stoppers for teeming in the usual way, the ingot moulds being run on cars underneath the two nozzles, which are at such a distance apart that two moulds can be filled simultaneously. This arrangement, however, has not given such good results in practice as were anticipated, and has not been used to any extent.

A general arrangement of a modern open hearth plant is shown by the plan and elevation (Plate xv.) of the Homestead plant as erected in 1898.* The furnaces are arranged in two lines as in the plant of 1890, with casting sides facing each other, the space between them being covered by two groups of overhead travelling cranes. The furnaces themselves and the charging sides are covered by a 40-ton crane handling a ladle for conveying molten metal from a metal mixer, and a 15-ton crane employed for handling materials, and for repairs, &c.

The furnaces, of 45 tons, are built on solid brick bottoms on the ground level, and in front of each is a ladle pit for lowering the ladle beneath the metal spout during tapping. The air and gas regenerative chambers are exceptionally large, being 22 feet long inside measurement and 14 feet 2 inches high to the top of the arch, and the air 10 feet and the gas 6 feet wide. The air chambers thus have a capacity of 65 cubic feet per ton of charge. Each furnace is provided with a separate stack, and at present natural gas is used, but every provision has been made so that producer gas can be employed should the necessity arise. The hearth of each furnace is 28 feet long and 13 feet 8 inches wide, and is built up first with a course of firebrick, then a course of chrome, followed by one course of Magnesite bricks, upon which loose basic material is burnt.

The casting ladles for each line of five furnaces are handled by a 75-ton Morgan electrical travelling crane with a span of 37 feet 8 inches and a hoisting speed of 12 feet per minute. On the lower flanges of the girder, as will be seen by reference to the elevation (fig. 180), runs a 25-ton auxiliary crane, so that jointly the two can handle 100 tons. This auxiliary crane has a hoisting speed of 25 feet per minute, and the speed of travel of the bridge is 200 feet per minute, hence it is most convenient for emptying the slag from the ladle into a slag bogie after the steel has been cast. This is expeditiously done by attaching a chain to the bottom of the ladle and using this auxiliary crane to tilt the ladle.

The hydraulic cranes and central casting pits of the 1890 plant have been superseded by the system of casting on cars, and along the centre of the main building are two pouring tracks, one on each side, on which the ingot moulds travel, and two double teeming platforms are provided, with appliances for casting on either side. These consist of a car-pusher operated by

* Taken from a sketch in the *Iron Age*.

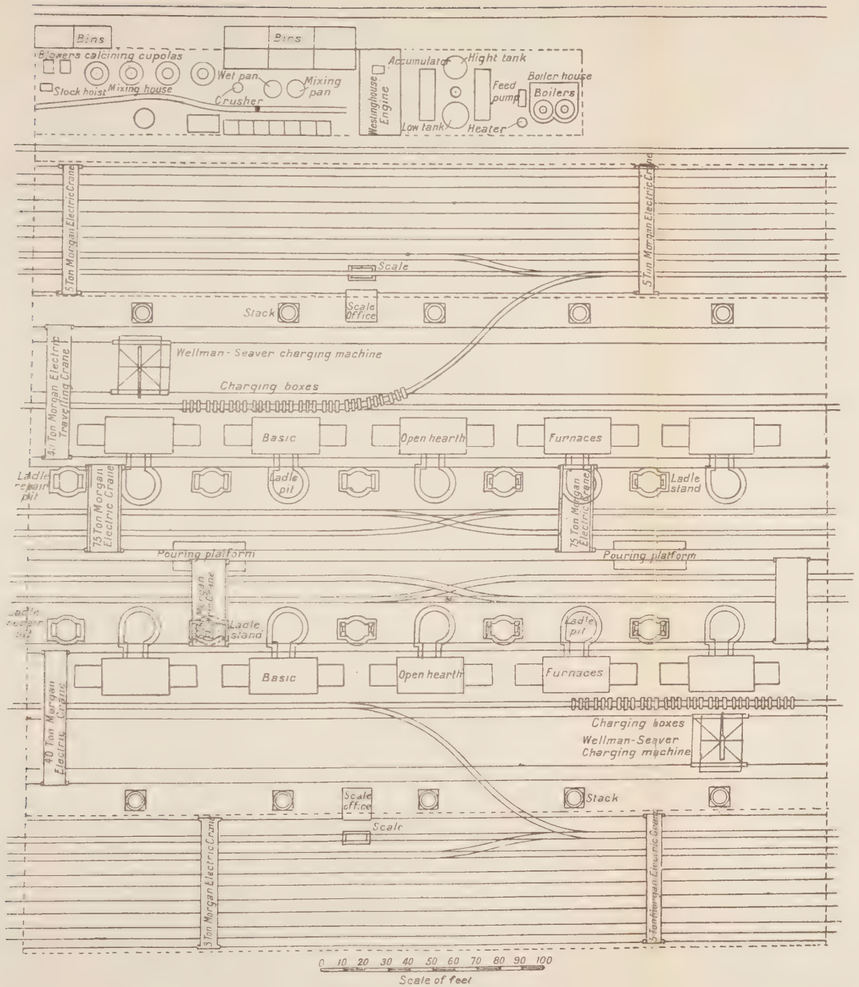


Fig. 179.—Plan of Homestead Open Hearth Plant.

PLATE XV.—Homestead Open Hearth Plant.

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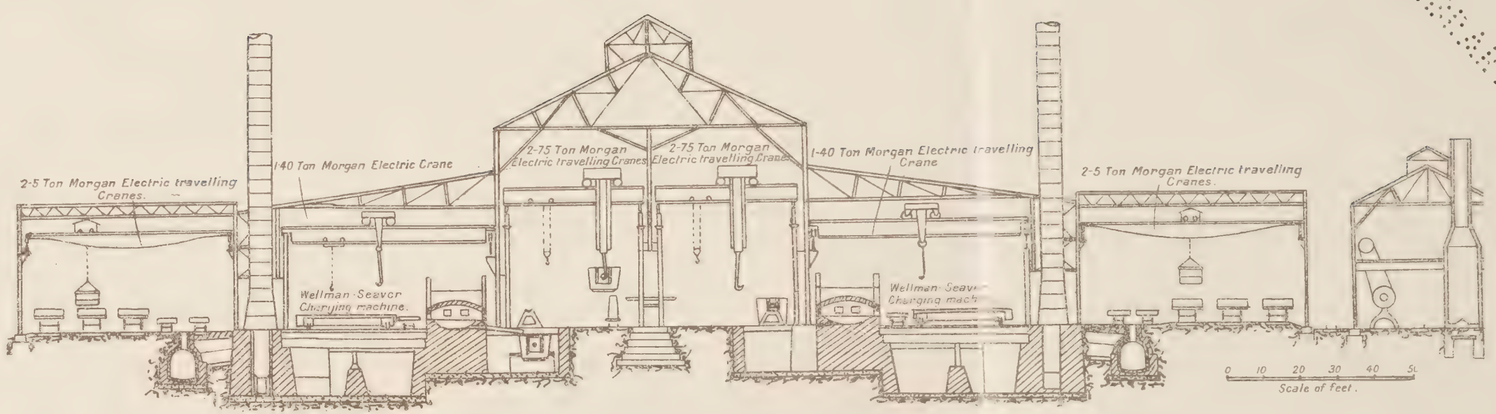

2-5 Ton Morgan Electric travelling Cranes.
140 Ton Morgan Electric Crane
2-75 Ton Morgan Electric travelling Cranes.
2-75 Ton Morgan Electric travelling Cranes.
140 Ton Morgan Electric travelling Crane
2-5 Ton Morgan Electric travelling Cranes.
Wellman-Seaver Charging machine.
Wellman-Seaver Charging machine.
0 10 20 30 40 50
Scale of feet.

Fig. 180.—Tranverse Section through Homestead Open Hearth Plant, showing overhead casting cranes for casting on cars

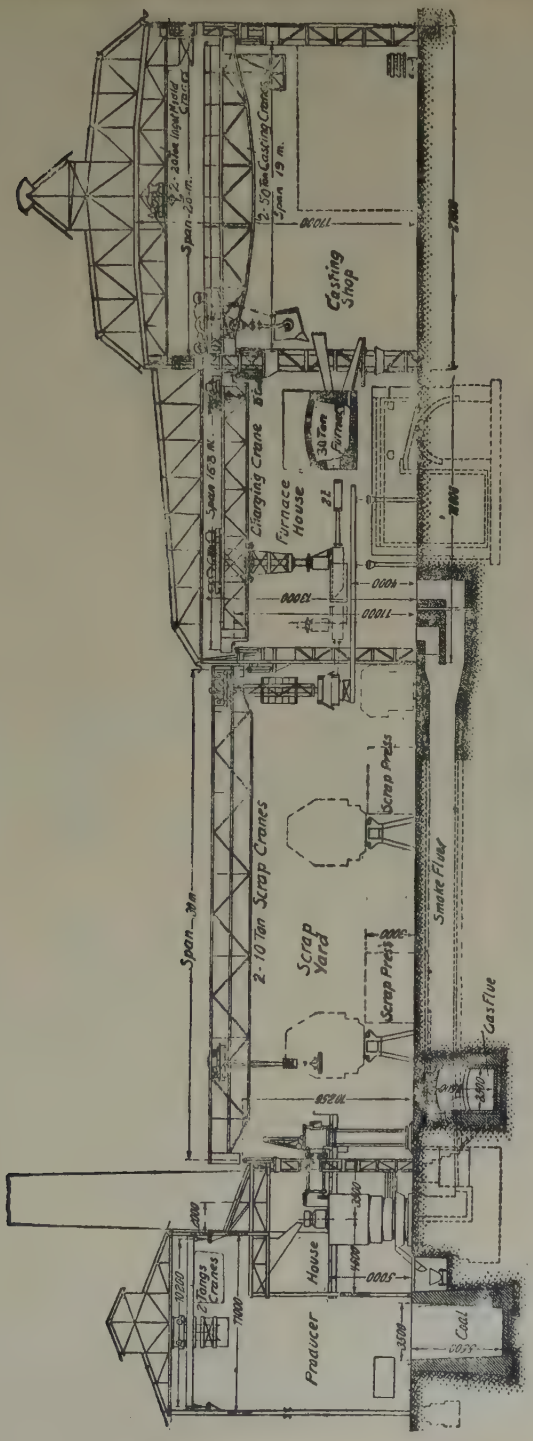


Fig. 181.—Sectional Elevation of New Plant at Bethlen-Falva Works.

a hydraulic cylinder with 14-feet stroke and 8 inches in diameter, with mechanism for engaging the dog which moves the car.

After teeming, the ladle is transferred to a ladle-stand, of which there are four to each group of five furnaces, for removing skulls and repairs.

The charging of the furnace is done by a Wellman charging crane running on a wide gauge track, and along the line of furnaces in front of the charging machine runs a narrow gauge track upon which travel cars with the charging boxes. On both sides of the main building parallel to the line of furnaces is a storage yard with three wide gauge standard tracks and two narrow gauge tracks. This yard is commanded from end to end by a 5-ton travelling crane with 58 feet 3 inches span, a hoisting speed of 50 feet, and speed of travel of 600 feet per minute.

Running parallel to the storage yard on one side of the main building is the basic shop, as shown in the plan, where the basic material is burnt, crushed and mixed, ready for delivery to the steel works. For calcining the basic material four 10-feet cupolas, 20 feet high to the charging door, are used.

Fig. 181 is a transverse sectional elevation of the new basic open hearth plant at Bethlen-Falva Works arranged for molten mixer metal. At this works large quantities of scrap are used, which is compressed in scrap presses it a shop behind the melting shop previous to charging. The open hearth furnaces are 30 tons, and the mixer is a tilting furnace holding 150 tons

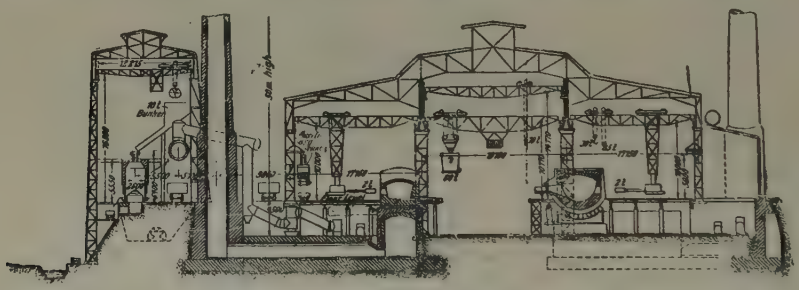


Fig. 182.—Transverse Sectional Elevation of Georgsmarienhutte Open Hearth Plant, showing Open Hearth Furnaces and Mixers.

Fig. 182 is a transverse sectional elevation of another basic open hearth plant, showing position of furnaces and mixer and general arrangement for charging both mixer and furnaces. This plant, Georgsmarienhutte, consists of five 40-ton open hearth furnace and one 150-ton mixer, but a second mixer of the same size is being erected. At this works the mixers are really worked as a Talbot furnace, the metal being completely desiliconised and the Phosphorus reduced from 0·6 per cent. to 0·10 per cent., and the metal then transferred to the open hearth furnace to complete the dephosphorisation and decarburisation to the required extent, when the metal is tapped.

Comparison of Bessemer and Open Hearth Processes.

Quality of Metal Produced.—The first consideration is the question of quality, and here it must be admitted that acid processes have the advantage over basic processes working under ordinary conditions, as, assuming care is taken to select suitable pig-iron, the risk of producing high Phosphorus

steel in the acid processes is at once eliminated, whereas, however great the care taken, the removal of the Phosphorus in the basic processes depends upon the skill and attention of the men, and there is always the possibility that the metal may not be dephosphorised to the required extent. In the case, too, of the manufacture of rails, or other fairly high Carbon steel in the converter, there is the additional risk of rephosphorisation from the slag on adding the recarburising material, even when every precaution is taken. With dead soft steel this danger exists in a smaller degree. In respect to removal of other impurities, the acid processes offer no advantages over the basic, as, in the removal of Sulphur, the advantage lies with the basic process, in which removal, if somewhat erratic, does frequently take place.

With regard to the open hearth process, where steels of different grades are required, with Carbon varying from ·100 to ·70 or 1·00, the acid process has again the undoubted advantage over the basic open hearth, as in working ordinary phosphoric pig-iron, recarburisation would have to be effected outside the furnace by some recarburising process, which does not enable the same control to be maintained as when it can be done in the hearth of the furnace. In the special case of working hematite iron in a basic furnace, the conditions are different, and we have the advantage of the pure iron used in acid furnaces, with the additional advantage that even the small percentages of Phosphorus originally present would be greatly reduced, and, consequently, an exceptionally pure material can be made.

The basic open hearth for treating hematite or low phosphoric pig-iron, although extending, has not come into general use, but the process is practically confined either to high phosphoric pig-iron, or pig-iron containing just too much Phosphorus for use in the acid open hearth. The reason for this is largely due to the fact that the majority of our English plants working the acid process have not blast furnaces in connection with their steel plants, and consequently cannot take molten mixer metal, but are confined to cold pig-iron, and in most cases this is high in Silicon, and would be very destructive of the furnace bottoms. Under conditions where hematite iron could be desiliconised in a mixer, there can be little doubt that the basic open hearth would be much more economical than the acid open hearth working cold materials, especially when the increased yield is taken into consideration. The improvement in the quality of the steel, especially in respect to low percentage of Phosphorus, would be undoubted, and there seems every reason why basic furnaces should be used in preference to acid, provided molten metal is obtainable, and it is probably only a question of time for them to be generally adopted.

Comparing the quality produced in the open hearth, whether acid or basic, with that of the Bessemer processes, there can be no doubt that the former produces a more regular and reliable material. In the first place, the operations are under greater control. Samples can be taken at repeated intervals, and examined if necessary, both chemically and mechanically, and the working of the process modified to produce the desired result. There is also far less danger of over-oxidation. That the quality of open hearth steel is, for the same class, superior to Bessemer, is confirmed by the fact that engineers, as the result of experience, always prefer it, and are prepared to pay a higher price for it. For high Carbon steels which have to conform to rigid specifications, the acid Siemens is almost exclusively employed, as experience has shown that it is extremely difficult to get the exact Carbon percentage specified by the other processes. Exception to this may be made in a few cases of small Bessemer plants in Sweden and this country, working

under special conditions as to the regularity and quality of their pig supply, and the smallness of their charges; but, speaking generally, the statement is correct.

Yield of Metal.—Here the open hearth processes have a considerable advantage over the Bessemer. The average yield of an acid Bessemer plant making rail steel will vary from about 86 to 88 tons of steel ingots for every 100 tons of metal (including pig, scrap, spiegel, &c.) used; and a basic Bessemer will yield only about 83 tons of ingots, whereas the acid open hearth, working with cold pig-iron and scrap, will yield about 97, and the basic about 95·0 tons of ingot per 100 tons of metal charged into the furnace. One reason why the yield in the basic processes is lower than the acid, is that the chemical loss due to presence of Phosphorus and more Manganese is greater. In modern basic open hearth practice where mixer metal of regular quality is taken molten to the basic open hearth furnace the yield should be at least 100 tons of ingots for each 100 tons of pig and scrap charged and in some cases will average as much as 102 to 103 tons.

Cost of the Acid and Basic Processes.—Both the labour costs and the costs as regards renewals of linings, repairs, and general refractories, must always be higher in the basic than in the acid processes: but against these disadvantages must be put the lower cost of pig-iron and scrap and the value of the basic slag produced. For the same size of plant, on the other hand, the output of the acid processes will be greater.

Comparison as to Cost.—It is extremely difficult to give fairly comparative costs, as prices at the same time vary very much in different districts, especially the price of scrap. At normal times, however, in the same district, the differences in price of hematite pig-iron and good basic iron will vary from 6s. to 8s. per ton in favour of the latter, although common phosphoric pig-iron, as used in some Bessemer plants, may sometimes be obtained for 10s. per ton less than hematite. It is, however, doubtful if there is any real advantage in using an iron of this class, as extra waste, &c., probably more than neutralises any gain in price. The difference in price of selected scrap suitable for open hearth acid work, and the miscellaneous wrought-iron and steel scrap which can be used in the basic open hearth will, in many cases, be 10s. per ton, and may be taken generally as at least 5s.

Taking the above as roughly representing the difference in the cost of materials to-day with present prices of labour and fuel, after allowing for all incidental and establishment charges, there is little difference in the cost of producing ingots by the various processes.

After crediting basic steel with the value of slag produced per ton of ingots, provided sufficient scrap can be obtained to work 30 per cent. in the charges, ingots can probably be produced more cheaply by the basic Siemens process than by any other.

The difference in cost of production by the acid and the basic Bessemer is so little, that it is almost impossible to say which has the advantage, although it is probable that the basic is slightly the cheaper.

The acid Siemens costs of production are probably a little higher than any of the others, although they are only slightly so, and, provided a good supply of scrap equal to 30 per cent. of the charges can be obtained, the difference is very slight.

Any slight variation in price of scrap, of course, at once alters the cost of production, and this is one of the difficulties attending Siemens work, in many districts it being almost impossible to get a good supply of high-class quality in sufficient quantity.

The costs of production in the modifications of the Siemens processes, such as the Talbot and Bertrand-Thiel processes, are difficult to obtain. In the case of the Bertrand-Thiel no entire plant has been designed to carry out the process under the best conditions, and the works using the process are working under disadvantages, but, in view of the fact that it has not been more generally adopted, presumably the advantages over the ordinary open hearth process cannot be so great as was anticipated. The Talbot process is now in use at various works in England and America, and appears to be making steady, if somewhat slow, progress. Judging from the small amount of reliable information available, the costs appear to be distinctly lower than in the ordinary open hearth working under the same conditions, especially when low Sulphur iron is available, and the chief objection to the process is the cost of the installation, which probably has been the principal reason why it has not been more generally adopted. At first the cost of repairs to the ports and furnaces was very heavy, but it has been considerably reduced by gradual improvements in construction.

In comparing the advantages and disadvantages of different methods of manufacture, the most important points for consideration in the selection of a particular process are the local conditions, first as to the supply of the raw materials, and, secondly, the material it is desired to make, whether rail steel, dead soft steel, or steels of different percentages of Carbon to meet the requirements of various specifications. Thus in some parts of England and on the Continent the only pig-iron which can be manufactured locally is a Phosphoric one, and the cost of production is such compared to the cost of imported hematite pig-iron that any process depending upon the latter would be most seriously handicapped, and this would practically settle the question as to some basic process, capable of dephosphorising, being adopted. The percentage of Phosphorus in the pig-iron, whether 2·2 per cent. or more, would largely decide the question whether the process should be the Bessemer or the open hearth. Given a cheap pig of over 2·2 per cent. of Phosphorus, especially if there was a demand for rails, the basic Bessemer would probably better meet the conditions, but with less Phosphorus than this the basic open hearth process in some form would have to be adopted.

With regard to the basic Bessemer, one great difficulty connected with the process is to obtain iron ores containing sufficient Phosphorus to make a pig-iron with a minimum of 2·2 per cent. of Phosphorus, as although Phosphoric ores are very widely distributed, they rarely contain sufficient Phosphoric acid to produce a pig-iron with this quantity of Phosphorus, and consequently we are not likely to see any new basic Bessemer plants started.

On the other hand, assuming hematite pig-iron of good quality can be obtained at a price within a few shillings per ton of the price of basic pig-iron, the acid open hearth would certainly be selected, especially if it is desired to make all classes of Carbon steels. The advantages of the acid open hearth over the Bessemer are such that the latter would never be adopted except in some special cases where it is desired to make one particular class of finished product, such as rail steel, and even then it is doubtful if it would be advisable to lay out a new works for this process.

The scarcity of high-class iron ores capable of producing a pig-iron with less than 0·06 per cent. of Phosphorus suitable for acid Bessemer work is becoming greater and greater, and acid steel rail makers are finding it more and more difficult to obtain pig-iron at a price which they can afford to pay. For high-class steels for special purposes the acid Siemens will continue

to be used, as in such cases specially selected pig-irons low in Phosphorus can be worked, the cost of the pig-iron not being such a serious question, as the price obtained for the finished product is so much higher.

It seems probable that in the future the basic open hearth, or some modification of it, will gradually supersede both the basic and acid Bessemer, and to some extent the acid open hearth, both for structural and rail steel, as there are large deposits of ores which are just too Phosphoric for acid work, and which would make an ideal pig-iron for basic open hearth practice. From many of these ores a pig-iron with about ·15 to ·5 per cent. of Phosphorus would be produced, and such a pig-iron worked under basic open hearth conditions would undoubtedly produce a far better material than is on the average produced either by the acid or basic Bessemer, as with such content of Phosphorus in the pig-iron the risk of making steel high in Phosphorus would be practically *nil*, or at all events not so great as the risks incurred by using hematite iron dangerously near the limit allowed in acid open hearth practice.

The general use of liquid mixer metal for the basic open hearth process, and especially the considerable preliminary refining which is now effected in the mixer, has so increased the output and yield, that the cost of production has been considerably reduced, and to-day the basic open hearth processes are in a much stronger position than a few years ago, and everything points to the continued expansion of steel manufacture in this direction.

The following tables, taken from a very exhaustive paper by O Petersen,* illustrate the reactions occurring under different conditions of basic open hearth practice, and in the Bertrand-Thiel and Talbot processes :—

* *Stahl und Eisen*, January, 1910, Nos. 9 and 10; *Iron and Coal Trades' Review*, January 21, 1910, *et seq.*

Tables illustrating Reactions and showing Yields, &c., in Basic Open Hearth and similar Processes.

TABLE XXXVI.—Chemical Changes during the Hoesch Process.

	Sample taken at	Period.	Analysis of the Metal, per cent.					Analysis of the Slag, per cent.								Charge and Adjuncts.	Remarks.
			C.	P.	Mn.	Si.	S.	FeO.	MnO.	Al_2O_3.	CaO.	MgO.	P_2O_5.	S.	SiO_2.		
Charge No. 1,465	12.1	1st period.	3·28	1·86	0·96	0·32	0·132	...	...	...	...	...	...	...	...	Charge: 23,280 kg. pig; 1,880 kg. lime; 3,440 kg. Swedish ore; 770 kg. rolling mill scale.	Pig run in.
	1.1		2·47	0·590	0·17	Trace	0·102	...	...	...	...	...	...	...	...		
	1.3		1·90	0·470	0·22	...	0·098	10·25	5·03	1·36	41·56	4·32	22·85	0·069	12·20		
	1.4		1·65	0·370	0·22	...	0·098	7·06	4·96	1·38	45·48	4·00	22·36	0·124	11·80		
	2.30		1·46	0·260	0·34	...	0·082	4·67	3·93	1·60	48·86	4·00	22·13	0·138	11·40		
	2.0		...	...	...	...	...	...	...	...	...	...	...	...	...	Charge: 2,182 kg. Spathic ore; 5,412 kg. scrap; 1,290 kg. lime.	End of 1st period. Metal returned to furnace.
	3.50	Finishing period.	0·385	0·090	0·29	...	0·100	19·64	13·49	3·17	33·64	6·92	6·25	0·110	14·20	Adjuncts: 105 kg. rolling mill scale.	
	4.10		0·205	0·050	0·23	...	0·089	15·78	12·08	3·00	35·78	6·70	6·70	0·165	15·40		
	4.30		0·090	0·045	0·26	...	0·090	15·83	8·88	2·32	43·88	6·00	5·50	0·289	13·20		
	4.45		0·075	0·035	0·26	...	0·080	14·13	10·19	2·21	43·79	6·10	5·57	0·206	14·20	160 kg. lime; (4·55) 206 kg. lime.	
	5.5		0·058	0·035	0·27	...	0·078	16·23	8·32	2·20	45·30	5·90	5·55	0·275	14·00		
	5.10		0·045	0·030	0·25	...	0·077	17·20	7·67	2·00	46·19	6·12	5·15	0·316	13·10		
	5.15		0·080	0·040	0·47	...	0·067	17·03	10·25	1·90	46·28	5·92	5·00	0·344	12·40	200 kg. Ferro-Manganese.	Tapped.

The above tables show reactions, &c., in the Hoesch process, which is worked in two stages, the metal being largely dephosphorised during the first period, then tapped into a ladle to separate the slag, and returned to same furnace for final removal of Phosphorus and conversion into finished steel. The furnaces used are from 30-ton capacity, and average output is 60 tons per twelve hours.

Metallurgically, this method of working is identical with the Bertrand-Thiel process. During the first period the metal is largely dephosphorised, as much Carbon being retained as possible, and, instead of being transferred to a finishing furnace, it is tapped into a ladle and returned to the same furnace without the phosphoric slag, a new slag is made and the heat finished in the usual way.

TABLE XXXVII.—Production and Consumption (Hoesch Process).

Charge (exclusive of Ore).								Output.		Iron per Ton of Sound Ingots.	Furnace Shifts.	Charges	Charges per Furnace Shift.	Sound Ingots.		Hard Steel Charge.
Basic Iron.	Hematite.	Spiegeleisen.	Ferro-Manganese.	Ferro-Silicon.	Scrap Iron.	Steel Scrap, &c.	Charge.	Sound Ingots.	Yield per cent. of Charge.					Per Day.	Per Charge.	
Kg. 36,209.647	Kg. 4,600	Kg. 120,950	Kg. 404,848	Kg. 7,080	Kg. 83,800	Kg. 11,631,695	Kg. 48,462,620	Kg. 50,605,965	104·42	Kg. 957·67	845·5	1,711	2·02	Kg. 119,474	Kg. 29,570	23
36,214,247 kg.		Per cent.	Per cent.	Pr.cent.	Per cent.	Per cent.										
74·72 per cent.		0·25	0·84	0·02	0·17	24·00										
Of Charge.																

Consumption of	Kg.	Per 1,000 Kg. Sound Ingot.
Ore and rolling mill scale,	11,010,565	217·5
Coke,	177,060	3·0
White lime,	4,749,275	94·0
Producer coal,	12,550,672	248·0
Basic material,	1,951,920	39·0
Boiler brick,	161,858	3·0
Firebrick,	422,506	8·0
Dinas brick,	942,321	19·0
Welding-furnace brick,	229,977	4·0
Flue brick,	270,882	5·0
Magnesite brick,	46,089	1·0
Chamber brick,	126,877	2·0
Ladle lining,	402,827	7·0
Fine sand,	277,444	5·0

Slag produced in 1st Period, and ground to Phosphate Meal.

6,376 *t* with 20 to 25 per cent. P_2O_5 = 126 kg. per ton of ingots.

Slag from 2nd Period, used in Blast Furnaces.

7,439 *t* = 147 kg. per ton of ingots.

Analysis.—

Molten Basic Iron from Mixer—
3·20 per cent. **C**; 1·82 per cent. **P**; 1·05 per cent. **Mn**; 0·41 per cent. **Si**; 0 084 per cent. **S.**

Metal at End of 1st Period—
1·95 per cent. **C**; 0·15 per cent. **P**; 0·36 per cent. **Mn**; traces **Si**; 0·07 per cent. **S.**

Slag from 1st Period—

	Per cent.		Per cent.		Per cent.		Per cent.
Fe	4·63	**CaO**	41·91	SiO_2	11·00	**MgO**	7·20
Mn	4·76	P_2O_5	24·93	Al_2O_3	2·10	**S**	0·36

Slag from 2nd Period—

	Per cent.		Per cent.		Per cent.		Per cent.
Fe	14·10	**CaO**	40·13	SiO_2	13·20	**MgO**	7·50
Mn	8·54	P_2O_5	7·47	Al_2O_3	2·99	**S**	0·44

Mild Steel—
0·07 per cent. **C**; 0·02 per cent. **P**; 0·44 per cent. **Mn**; 0·055 per cent. **S.**

Composition of Ore used—

	Rolling Mill Scale. Per cent.	Spathic Ore. Per cent.	Swedish Ore. Per cent.	Minette. Per cent.
Fe	72·34	47·18	63·7	34·98
Mn	0·57	8·21	0·2	0·28
P	0·02	0·06	1·5	0·70

TABLE XXXVIII.—Chemical Changes in Charge 4,850 (Hubertushütte).

Sample taken at o'clock.	Analysis of Metal, per cent.					Analysis of Slag, per cent.					Charges and Adjuncts.	Remarks.
	C.	Mn.	P.	Si.	S.	SiO_2.	CaO.	FeO.	MnO.	P_2O_5.		
12.45	...	...	...	...	...	...	...	...	...	...	22,400 kg. pig (3·61 per cent. **C**, 2·32 per cent. **Mn**, 1·89 per cent. **Si**, 0·044 per cent. **S**, 0·67 per cent. **P**). 4,700 kg. Swedish magnetic ironstone. 900 kg. South Russian ore.	Furnace charged.
1.45	2·72	0·038	0·050	0·500	0·030	20·99	...	33·25	10·86	7·33		Bath hot and boiling.
2.15	2·45	0·046	0·035	0·050	0·030	20·98	...	33·70	11·00	7·30		,, ,, frothing commences.
2.45	2·34	0·046	0·027	0·031	0·028	21·15	...	30·14	11·29	6·96	Adjuncts :	Bath hot and frothing.
3.15	1·94	0·054	0·020	0·042	0·026	22·35	...	24·47	11·68	7·59	Lime, 3 to 4 per cent. .	Bath frothing, but cooler.
3.45	1·76	0·061	0·040	0·065	0·026	23·66	...	19·02	11·91	7·81		,, ,, cold.
4.15	1·68	0·084	0·044	0·033	0·030	23·83	...	15·57	12·24	7·95		,, ,, ,,
4.45	1·17	0·154	0·065	0·053	0·026	24·55	...	11·12	12·19	7·40		Bath cold ; frothing subsides.
5 0	1·14	0·199	0·094	0·035	0·034	25·76	...	9·57	11·80	7·21	. . . . .	Bath grows hotter and boils.
5.15	0·82	0·261	0·140	0·017	0·028	...	Not tested.	...	...	...	. . . . .	,, ,, ,,
5.45	0·71	0·307	0·138	0·015	0·028	22·67	...	7·44	10·43	6·41	400 kg. South Russian ore. .	Bath is hot and boils.
6.0	0·61	0·192	0·051	0·031	0·040	21·32	...	11·46	9·67	5·43	. . . . .	,, ,,
6.20	0·375	0·253	0·019	0·015	0·036	22·56	...	9·90	9·28	6·89	400 kg. South Russian ore. .	,, ,,
7.0	0·090	0·261	0·059	0·010	0·030	21·87	...	10·57	8·38	6·30	. . . . .	Sample is sufficiently mild.
7.15	0·084	0·269	0·035	0·020	0·038	21·17	...	10·34	7·95	6·21	160 kg. Ferro-Manganese. .	
7.30	0·087	0·499	0·067	0·004	0·042	20·29	...	9·45	9·24	5·73	. . . . .	Furnace tapped.

Table xxxviii. shows the chemical changes during the working of very silicious molten blast-furnace metal charges at Hubertushütte. The furnaces are of 20- and 25-ton capacity. It will be noticed that the slag is very silicious, and consequently the Phosphoric Acid is not strongly held, and is frequently reduced and passes back into the metal during the working of the charge. The time of working such charge is $6\frac{3}{4}$ hours, and the average, with charge containing 1 per cent. or less of Silicon, $5\frac{1}{2}$ hours.

TABLE XXXIX.—Furnace Yield (Hubertushütte).

Average for the Year.	Percentage Yield. Added Ore included.			Percentage Yield. Added Ore not included.	
	Metal.	Slag.	Loss.	Sound Ingots.	Waste.
1905, . . . With 50 to 55 per cent. molten pig,	85·7	13·2	1·1	94 to 96 (according to quality of scrap iron).	3·0
1906, . . .					
1907, . . .					
1908, . . .					
1909 (6 months),					
Charge all molten pig, .	85·0	13·8	1·2	101·85	3·15

Table xxxix. shows difference in yield when using 50 per cent. scrap and all pig-iron.

TABLE XL.—Consumption of Material (Weight per cent. of Sound Ingots), (Hubertushütte).

Average for the Year.	Iron Ore.	Quicklime.	Coal.	Calcined Dolomite.	Sintered Magnesite.	Ingot Moulds. Cost per Ton of Ingots.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	s.
1905, . .	13·0	4·8	35·6	4 to 6	0·1	1·65
1906, . .	14·8	3·3	31·8			1·57
1907, . .	15·9	4·0	25·0			1·52
1908, . .	11·7	3·6	18·7			1·59
1909 (6 months),	11·6	4·7	17·0			1·62

The low coal consumption shown in Table xl., after 1906, is due to use of coke-oven gas, and the furnaces have been heated with this since that date.

TABLE XLI.—Chemical Changes in Charge No. 3,033 (Julienhütte).

Sample taken at o'clock.	Analysis of Metal, per cent.					Analysis of Slag, per cent.								Charges and Adjuncts.	Remarks.
	C.	P.	Mn	Si.	S	FeO.	MnO.	Al_2O_3.	CaO.	MgO.	P_2O_5.	S.	SiO_2.		
Mixer Iron	3·610	0·410	2·10	1·21	0·050	...	...	...	...	...	...	...	...	7,210 kg. Krivoi-Rog ore, 1,000 kg. lime.	
1.10	...	...	...	...	...	41·30	10·56	2·40	14·86	7·14	3·50	0·061	20·20	32,100 kg. pig and 8,170 kg. turnings.	Charge frothing.
1.40	...	...	...	...	...	42·04	10·15	1·40	15·40	7·05	3·85	0·066	20·05		
2.0	...	...	...	...	...	44·75	9·04	2·15	15·29	6·34	3·73	0·060	18·50		
2.45	0·730	0·066	0·06	Traces	0·037	25·38	9·11	3·40	23·89	9·03	4·03	0·068	24·60		
3.25	0·635	0·048	0·10	,,	0·029	16·23	9·19	4·50	32·06	8·41	3·50	0·057	25·70	370 kg. lime.	All melted.
3.40	0·497	0·052	0·13	,,	0·030	13·65	8·70	4·08	34·47	7·80	3·57	0·075	26·98	490 ,, ,, 255 kg. ore.	Charge begins to boil.
3.55	0·386	0·042	0·15	,,	0·037	13·51	7·67	3·74	36·89	7·87	3·57	0·068	26·70	560 ,, ,, 340 ,, ,,	Charge boils
4.10	0·272	0·032	0·14	,,	0·038	14·73	7·50	5·05	35·98	7·80	3·71	0·066	24·80	210 ,, ,,	freely.
4.20	0·211	0·036	0·17	,,	0·035	14·19	6·87	4·80	39·08	7·51	3·37	0·068	23·70	170 ,, ore.	
4.35	0·142	0·035	0·17	,,	0·030	13·37	7·36	3·95	39·97	7·76	3·50	0·078	23·90	110 ,, lime.	
4.45	0·104	0·032	0·19	,,	0·027	13·24	6·87	4·22	39·69	7·99	3·37	0·075	23·90	120 ,, ,,	
5.0	0·088	0·029	0·19	,,	0·030	13·37	6·25	4·28	42·97	7·44	3·21	0·068	21·86	165 ,, Ferro-Manganese.	Charge quiet.
5.10	0·113	0·034	0·45	,,	0·030	12·69	7·60	4·26	43·89	6·90	3·24	0·068	20·85		Furnace tapped.
Sample of finished steel.	0·105	0·036	0·43	,,	0·035	...	...	...	...	...	...	...	...		

Charge introduced, . . 11.20 o'clock.
Pig-iron run in, . . . 12.30 ,,
Tapped, ... 5.10 ,,

Yield,		
. . .	39,490 kg. sound ingots	= 98·06 per cent.
	970 ,, casting ingots	= 2·41 ,,
Total yield, .	40·460 ,,	100·47 ,,

Table xli. shows chemical changes taking place during the working of charge of medium Silicon iron from the mixer. At this works, the mixer is simply used to store the metal, remove about 30 per cent. of the Sulphur, and desiliconise to a small extent.

TABLE XLII.—Chemical Changes in Charge No. 5738 (Jurievka Works).

Sample taken at o'clock.	Analysis of Metal, per cent.					Analysis of Slag, per cent.								Charge and Adjuncts.	Remarks.
	C.	P.	Mn.	Si.	S.	FeO.	MnO.	Al_2O_3.	CaO.	MgO.	P_2O_5.	S.	SiO_2.		
7.15	4·20	0·15	2·50	1·10	0·06	...	...	...	...	...	...	...	...	6,314 kg. ore and 2,132 kg. limestone. . . .	Charging commenced.
7.40	4·44	0·08	2·28	0·88	0·03	...	...	...	...	...	...	...	...	} molten pig, 28,520 kg. {	Ladle I.
8.0	4·28	0·08	2·39	0·84	0·03	...	...	...	...	...	...	...	...		,, II.
8.30	2·04	0·03	0·11	Trcs.	0·02	33·28	17·03	5·61	20·50	2·59	1·15	0·38	19·52	.....	Charge froths strongly.
9.0	...	0·03	0·17	,,	0·01	24·89	16·24	10·00	23·00	3·09	1·31	0·33	21·52	.....	Charge gradually settles.
9.30	...	0·02	0·19	,,	0·02	20·07	16·34	9·09	27·60	3·53	1·21	0·27	22·44	492 kg. ore.	
10.0	0·95	0·02	0·21	,,	0·02	20·87	15·32	5·86	31·35	3·81	1·15	0·49	21·52	328 ,,	Charge quiet.
10.20	...	...	...	...	...	...	...	...	...	...	...	...	...	246 ,,	
10.30	0·55	0·03	0·25	,,	0·03	17·88	15·26	4·80	33·41	5·98	1·01	0·38	21·68	197 ,,	Charge froths slightly.
10.50	..	...	...	...	...	...	...	...	...	...	...	...	...	Two shovels of sand.	Charge quiet.
11.0	0·23	0·02	0·28	,,	0·02	14·62	13·58	5·69	36·50	7·49	0·92	0·27	21·50	262 kg. Ferro-Manganese (80 per cent.)	Charge throws up bubbles.
														49 kg. Ferro-Manganese at 11.20 o'clock.	Charge boils quietly.
11.30	0·08	0·04	0·58	,,	0·04	10·76	15·05	6·27	37·52	8·43	0·73	0·33	20·80	.....	Furnace tapped.

Yield: Sound ingots 28,011 kg. = 102·2 per cent.; Casting waste 508 kg. = 1·1 per cent.; Slag 4,084 kg.

Table xlii. shows the chemical changes during the working of low Phosphoric metal direct from the blast furnace at the Donetz-Jurievka Works in Russia. The blast-furnace metal gives an average analysis of Carbon, 4·2; Silicon, 1·1; Manganese, 2·5; Phosphorus, 0·15; and Sulphur, 0·06; and is so regular that although two mixers have been installed they are not required.

TABLE XLIII.—Technical Efficiency of the 30 to 35-Ton Furnaces (Jurievka Works).

Average for the Year.	No. of Charges per Furnace per Day.	Daily Output per Furnace.	Monthly Output.	Weight per Charge.	Annual Output of Ingots.
		Tons.	Tons.	Tons.	Tons.
1905, ...	4·0	100·2	11,220	25·1	134,200
1906, ...	3·9	108·3	11,310	27·7	135,600
1907, ...	3·7	109·8	11,230	27·7	134,350
1908, ...	3·8	114·0	12,810	30·0	153,610
1909 (6 months), . . .	4·2	129·0	16,550	30·7	...

TABLE XLIV.—Consumption of Materials (Jurievka Works). (Weights per cent. of Sound Ingots.)

Average for the Year.	Iron Ore.	Limestone.	Coal.	Calcined Dolomite.	Sintered Magnesite.	Ingot Moulds. Cost per Ton of Ingots.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	s.
1905, . .	22·8	7·8	23·4	4·5	0·16	2·1
1906, . .	20·4	8·2	22·5	4·4	0·15	1·7
1907, . .	21·0	8·3	24·8	4·3	0·15	1·8
1908, . .	21·3	8·1	25·4	3·9	0·22	1·9
1909 (6 months),	22·8	8 0	22·4	3·4	0·15	1·8

TABLE XLV.—Yield from Furnaces (Jurievka Works).

Average for the Year.	Percentage Yield (Total Charge, including Ore).		Percentage Yield (added Ore not included).		
	Metal.	Slag.	Sound Ingots.	Casting Waste.	Total Yield of Metal.
1905, ...	85·52	5·07*	101·40	4·98	106·33
1906, ...	86·26	5·96*	101·28	3·78	105·07
1907, ...	85·93	13·63	101·33	3·46	104·79
1908, ...	84·86	13·08	102·20	3·60	105·80
1909 (6 months), . . .	85·80	12·40	103·00	4·20	107·20

Tables xliii., xliv., and xlv. give particulars as to output, materials used, and yield for five years, 1905-1909, at the Donetz-Jurievka Works, Russia.

* Data estimated, slag having been thrown away.

TABLE XLVI.—Yield from Combined Process (Witkowitz).

Average for Years.	Yield in per Cent.				
	Added Ore Included.			Added Ore not Included.	
	Metal.	Loss.	Open-hearth Slag.	Sound Ingots.	Pouring Waste.
1904-5 . .	87·14	12·86	10·09	90·73	4·09
1905-6 . .	87·07	12·93	12·17	90·81	3·23
1906-7 . .	86·52	13·48	12·59	89·42	3·28
1907-8 . .	87·00	13·00	11·46	89·43	3·97
1908-9 . .	87·12	12·88	10·39	89·25	2·11

TABLE XLVII.—Technical Efficiency of Furnaces (Witkowitz).

Average for Years.	No. of Daily Charges per Furnace.	Daily Output per Furnace.	Monthly Output per Furnace.	Weight of Charge.	Annual Output of Ingots.
		Tons.	Tons.	Tons.	Tons.
1904-5 . .	6·7	135·7	3,528·2	20·1	127,857·1
1905-6 . .	6·7	136·2	3,541·2	20·1	127,093·8
1906-7 . .	5·8	117·7	3,201·4	20·2	134,560·1
1907-8 . .	5·8	114·8	3,099·6	19·8	150,650·6
1908-9 . .	6·0	121·4	3,277·8	19·9	157,553·1

TABLE XLVIII.—Consumption of Materials in Combined Process (Witkowitz).

Average for Years.	Weight in per cent. of Sound Ingots.					Ingot Moulds.
	Iron Ore.	Lime.	Coal.	Dolomite (Calcd.)	Magnesite (Sint.)	
						Kg.
1904-5, . .	4·0	5·9	14·7	3·64	0·20	1·30
1905-6, . .	4·7	6·3	14·1	2·51	0·20	1·23
1906-7, . .	3·7	7·2	15·0	2·34	0·24	1·34
1907-8, . .	3·1	7·4	14·3	3·10	0·28	1·43
1908-9, . .	2·7	7·8	10·5	2·67	0·31	1·31

Tables xlvi., xlvii., and xlviii. show the yield, consumption of material, and output from the Duplex process at Witkowitz.

The metal, which contains about 0·4 per cent. of Phosphorus, is blown in acid Bessemer converter to eliminate the greater part of the Carbon, Silicon, and Manganese, and then this refined metal is converted into finished steel in a basic open-hearth furnace.

The refined metal, after Bessemerising, has the following composition :— Silicon 0·04 to 0·06, Manganese 0·25 to 0·35, Carbon 0·10 to 0·20, and Phosphorus 0·30 to 0·50 per cent.

The Talbot Process.

TABLE XLIX.—Chemical Changes in Charge B, Cargo Fleet, 16th Nov., 1909.

Time o'clock.	Analysis of the Metal, per cent.					Analysis of the Slags, per cent.			Charges and Adjuncts.	Remarks.
	C.	P.	Mn.	Si.	S.	SiO_2	FeO.	MnO.		
2.25	0·08	0·038	0·17	...	0·048	...	...	...	.....	About 120 tons metal in furnace.
2.45	...	...	...	...	...	11·70	14·01	6·32	.....	Furnace walls repaired, 12 tons of slag drawn off.
3.5	...	...	...	...	...	...	...	...	9,140 kg. Gellivara ore, 3,450 kg. lime.	
3.15	3·30	1·650	0·70	1·13	0·061	...	...	...	22,350 kg. molten pig.	
4.40	0·05	0·013	Trace	...	0·050	10·40	22·37	4·09	.....	
4.45	...	...	...	...	...	...	...	...	2,030 kg. purple ore, 2,130 kg. lime.	
5.5	3·30	1·22	...	1·17	0·059	...	...	...	20,320 kg. molten pig.	
6.15	3·30	1·22	...	1·17	0·059	...	...	...	15,240 ,, ,,	
6.50	...	...	...	...	...	...	...	...	865 kg. lime.	
7.0	0·55	0·018	...	0·039	0·083	11·90	13·24	7·64	.....	
7.10	...	...	...	...	...	...	...	...	865 kg. lime.	
7.20	0·45	0·150	...	...	0·050	...	...	...	.....	
7.30	...	...	...	...	...	...	...	...	1,020 kg. rolling mill scale.	
8.0	...	...	...	...	...	...	...	...	1,320 kg. purple ore.	
8.5	0·26	0·030	...	...	...	...	...	...	.....	
8.30	...	...	...	...	...	...	...	...	1,520 kg. Gellivara ore, 430 kg. lime.	
9.0	...	...	...	...	...	...	...	...	Duration of charge between tappings, 6 hrs. 35 min.	About 55 tons of steel drawn off in ladle with 430 kg. Ferro-Manganese (80 per cent.), 51 kg. Ferro-Silicon (50 per cent.), and Anthracite.
9.10	0·10	0·019	...	3·047	0·033	10·80	14·14	6·32	Composition of finished steel: 0·55 per cent. **C**, 0·68 per cent. **Mn**, 0·026 per cent. **P**, 0·041 per cent. **S**.	

Table xlix. shows the chemical changes during the working of the charges by the Talbot process.

The Talbot Process.

TABLE L.—Chemical Changes in Charge C, Cargo Fleet, 16th Nov., 1909.

Time o'clock.	Analysis of the Metals, per cent.					Analysis of the Slag, per cent.			Charges and Adjuncts.	Remarks.
	C.	P.	Mn.	Si.	S.	SiO_2.	FeO.	MnO.		
11.50	0·16	0·046	0·019	...	0·048	...	...	...	.....	About 120 tons metal in furnance.
12.0	...	...	...	...	...	9·20	15·15	5·58	.....	Furnace walls repaired, 8 tons of slag drawn off.
12.20	...	...	...	...	...	...	...	...	4,570 kg. Gellivara ore, 2,130 kg. lime.	
12.30	3·65	1·660	0·77	1·39	0·044	...	...	...	22,350 kg. molten pig.	
12.55	0·40	0·058	Trace	...	0·037	9·00	20·57	4·83	.....	
1.0	...	...	...	...	...	...	...	...	4,570 kg. Gellivara ore, 2,130 kg. lime.	
1.10	...	1·560	...	0·93	0·067	...	...	...	22,350 kg. molten pig.	
1.30	...	1·600	...	0·65	0·086	...	...	...	8,130 ,, ,,	
2.20	0·65	0·088	Trace	...	0·048	11·20	14·77	2·60	.....	
2.25	...	...	...	...	...	...	...	...	1,020 kg. purple ore, 1,270 kg. lime.	
2.30	...	...	...	...	...	...	...	...	1,020 kg. Gellivara ore, 860 kg. lime.	
2.40	0·50	0·080	...	...	...	...	...	...	.....	
2.45	...	...	...	...	...	...	...	...	860 kg. lime.	
3.15	0·39	0·040	...	...	...	...	...	...	.....	
3.40	0·28	...	...	...	...	...	...	...	.....	
3.55	0·22	...	...	...	...	...	...	...	.....	
4.0	...	...	...	...	...	...	...	...	860 kg. lime.	
4.20	0·21	0·011	...	0·036	0·032	13·20	13·24	6·32	Duration of charge between tappings, 4 hrs. 30 min. Composition of finished steel: 0·45 per cent. **C**, 0·68 per cent. **Mn**, 0·033 per cent. **P**, 0·040 per cent. **S**.	About 54 tons of steel drawn off in ladle with 430 kg. Ferro-Manganese (80 per cent.), 51 kg. Ferro-Silicon (50 per cent.), and Anthracite.

Table I. shows the chemical changes during the working of the charges by the Talbot process.

TABLE LI.—Weekly Record of a Talbot Furnace (175-Ton Furnace, Cargo Fleet).

Date.	Charge.	Molten Pig.					Scrap.	Iron Ore.	Rolling-Mill Scale.	Lime.	Dross.	Ferro-Manganese.	Ferro-Silicon.	Yield of Sound Ingots.	Composition of Finished Product.				Uses of the Iron.
		Weight.	Composition.												C.	S.	P.	Mn.	
			Si.	S.	Mn.	P.													
1909.	No.	Kg.					Kg.	Kg.	Kg.	Kg.	Kg.	Kg.	Kg.	Kg.					
Sept. 5	2,276	152,400	1·32	0·113	0·65	1·58	..	26,416	3,556	27,940	16,916	356	76	57,963	0·155	0·054	0·028	0·570	
,, 5	2,277	76,200					..	17,272	2,337	14,732	2,184	533	76	54,966	0·515	0·055	0·029	0·700	Rails.
,, 6	2,278	55,880					..	14,224	1,168	9,144	2,946	508	76	58,217	0·590	0·063	0·044	0·700	,,
,, 6	2,279	..	1·15	0·122	0·63	1·60	..	..	..	..	..	508	76	59.030	0·580	0·062	0·042	0·655	,,
,, 6	2.280	79,248					30,480	17,272	1,168	14,732	6,604	457	76	57,404	0·160	0·055	0·032	0·700	Construction work.
,, 7	2,281	50,800					10,160	13,716	2,337	8,128	2,946	381	76	54,610	0·185	0·058	0·030	0·660	,,
,, 7	2,282	..	1·09	0·107	0·69	1·83	..	..	..	..	..	381	76	54,610	0·180	0·058	0·032	0·686	,,
,, 7	2,283	76,200					32,512	14,224	3,556	14,732	5,893	457	76	58,217	0·370	0·058	0·029	0·733	Special steel.
,, 8	2,284	..	..	..	..	..	..	..	..	..	..	356	76	58,217	0·170	0·059	0·028	0·630	Construction work
,, 8	2,285	71,120					40,640	14,224	2,337	16,256	6,604	457	254	57,099	0·590	0·053	0·031	0·666	Rails.
,, 8	2 286	..	1·11	0·122	0·67	1·69	..	..	..	..	..	406	51	56.490	0·180	0·053	0·030	0·600	Construction work.
,, 8	2,287	76,200					35,560	2,032	1,168	11,648	7,620	356	76	57,404	0·196	0·058	0·041	0·656	,,
,, 9	2,288	..	..	..	..	..	..	..	..	..	..	356	76	58.979	0·180	0·058	0 040	0·600	,,
,, 9	2,289	83,360	0·96	0·111	0·69	1·63	30,480	17,272	2,337	15,748	3,658	381	51	55,626	0·190	0 056	0·030	0·670	,,
,, 9	2,290	55,880					..	17 272	2,337	12,700	2,184	457	76	58,217	0·590	0·054	0·026	0·733	Rails.
,, 10	2,291	60,960					..	14,224	1,168	11,176	5,080	483	51	56,033	0·590	0·052	0·023	0·750	,,
,, 10	2,292	..					..	..	..	..	..	483	51	56,033	0·570	0·051	0·023	0·790	,,
,, 10	2,293	86,360	1·13	0·101	0·67	1·61	25,400	17,272	1,676	15,748	9,950	483	76	58,217	0·590	0·060	0·029	0·725	,,
,, 10	2,294	..					..	..	..	..	..	432	76	60,808	0·180	0·060	0·028	0·620	Construction work.
,, 10	2,295	111,760					..	23,368	1,981	16,256	1,473	483	51	57,201	0·540	0·059	0·050	0·830	Rails.
,, 11	2,296	..	..	..	..	..	..	..	..	..	..	381	102	54,610	0·175	0·058	0·050	0·790	Construction work.
,, 11	2,297	15,240	1·06	0·104	0·69	..	..	..	..	..	..	381	102	53,289	0·160	0·053	0·030	0·525	,,
	22 Charges.	1,044,448	Time worked in the week 155 hours 15 minutes.				205,232	208,788	27,127	188,976	73,660	9,474	1,768	1,253,744	..	..	..	..	

Total, . . . 1,044,448 kg. molten pig
205,232 ,, scrap.
1,249,680 ,, metal charge.

208,788 kg. iron ore.
27,127 ,, rolling-mill scale.
73,660 ,, purple ore.
309,575 ,, added ore = 24 per cent. of the total weight of ingots produced.

22,352 kg. dolomite consumption = 1·78 per cent. of the yield of ingots.
188,976 ,, lime consumption = 15·06 per cent.
Total yield, . . . 1,253,744 ,, sound ingots + 17,780 kg. casting waste (= 1·3 per cent. of sound ingots = 101·7 per cent. total yield).

Table li. gives a summary of materials used, yield, &c., under normal conditions of working Talbot process.

TABLE LII.—Weekly Summary of Steel Output (Talbot Furnace at an English Works).

Metals.	Five Ordinary Open-hearth Furnaces.		Two Talbot Furnaces.			
			I. (100-ton).		II. (150-ton).	
	Kg.	Kg/t.	Kg.	Kg/t.	Kg.	Kg/t.
Pig iron,	876,300	602	659,892	868	688,949	842
Scrap,	550,672	379	...	...	108,407	133
Ferro-Manganese,	10,363	7	5,588	8	5,994	7
Hematite,	25,400	17	16,154	21	14,224	17
Cold pig,	48,869	34	...	...	10,160	12
Spiegeleisen,	8,585	6	7,010	10	12,294	15
Ferro-Silicon,	...	...	...	...	...	...
Total,	1,520,190	1,045	688,644	907	840,028	1,026
Sound ingots,	1,454,404	...	760,152	...	817,816	...
Slag,	...	...	247,244	325	247,243	302
Scrap waste,	...	...	5,436	...	4,674	...
Rolling-mill scale,	91,643	63	47,904	63	47,904	59
Hammer scale,	10,109	7	...	...	...	...
Gellivara ore,	106,578	73	164,795	217	175,869	215
Total,	208,330	143	212,699	280	223,774	274
Limestone,	224,739	157	...	..	...	...
Lime,	55,067	38	118,618	156	135,382	166
Yield, in per cent. of the metal charge,	95·68	...	*I. 110·4 = 111·2 with scrap.		†II. 97·36 = 97·95 with scrap.	
Coal Consumption,	42·7 per cent.		25·9 per cent.			

Table lii. gives a comparative summary of materials used, yield, &c., of five ordinary open-hearth furnaces and two Talbot furnaces.

* This yield is above the average. † This yield is below the average.

TABLE LIII.—Summary of the Working of Talbot Charges.

I.—Charges with Large Addition of Scrap.

Material.	Three Furnaces.		Three Furnaces.		Three Furnaces.		Three Furnaces.	
	Kg.	Per cent.	Kg.	Per cent.	Kg.	Per cent.	Kg.	Per cent.
Molten pig,	1,467,766	44·8	2,080,768	66·6	2,021,434	63·5	2,090,268	66·3
Cold pig,	96,520	2·9	73,152	2·3	20,320	0·6	93,472	3·0
Scrap,	1,673,352	51·2	940,816	30·1	1,110,488	34·9	937,768	29·6
Ferro-Manganese,	26,949	0·82	23,076	0·73	23,965	0·77	25,070	0·78
Ferro-Silicon,	4,800	0·14	4,356	0·13	3,873	0·12	3,023	0·09
Added ore,	239,776	7·2	467,360	14·6	488,696	15·0	567,944	17·6
Lime,	379,984	11·4	482,600	15·1	498,856	15·3	495,808	15·3
Dolomite,	48,768	1·5	97,536	3·0	66,040	2·0	92,456	2·8
Sound ingots,	3,267,456	100·0	3,161,792	101·2	3,203,448	100·7	3,168,904	100·6
Scrap,	53,848	1·5	26,416	0·9	54,864	1·7	62,992	2·0
Yield,	...	101·5	...	102·1	...	102·4	...	102·6

II.—Charges with Medium Addition of Scrap.

Molten pig,	2,648,052	81·3	2,556,256	74·8	2,470,912	76·7	2,550,160	72·2
Cold pig,	11,176	0·3	26,416	0·7	13,208	0·4	99,568	2·8
Scrap,	562,864	17·3	797,306	23·3	701,192	21·7	849,071	24·0
Ferro-Manganese,	29,290	0·9	29,337	0·86	29,388	0·91	30,176	0·86
Ferro-Silicon,	3,962	0·12	4,445	0·13	6,020	0·19	4,674	0·13
Added ore,	854,456	25·8	745,744	21·4	787,400	24·0	712,216	19·9
Lime,	582.168	17·6	618,744	17·8	558,800	17·0	483,616	13·5
Dolomite,	57,912	1·7	62,992	1·8	89,408	2·7	69,088	1·9
Sound ingots,	3,264,408	100·3	3,438,144	100·7	3,213,608	99·8	3,539,744	100·2
Scrap,	38,608	1·1	33,528	1·0	61,976	1·9	35,560	1·0
Yield,	...	101·4	...	101·7	...	101·7	...	101·2

III.—Charges with Very Small Addition of Scrap.

Material.	Two Furnaces.		Two Furnaces.		Two Furnaces.	
	Kg.	Per cent.	Kg.	Per cent.	Kg.	Per cent.
Molten pig,	2,134,616	97·0	2,154,396	97·1	1,969,372	91·9
Cold pig,	10,160	0·5	10,160	0·4	22,352	1·0
Scrap,	31,496	1·4	39,210	1·3	128,016	6·0
Ferro-Manganese,	19,304	0·87	20,076	0·94	19,558	0·93
Ferro-Silicon,	4,064	0·18	3,962	0·18	3,962	0·18
Added ore,	561,848	25·0	618,744	27·8	522,224	24·5
Lime,	392,176	17·4	371,856	16·7	352,552	16·5
Dolomite,	48,768	2·1	57,912	2·6	76,200	3·6
Sound ingots,	2,214,880	100·7	2,186,432	98·5	2,092,960	97·6
Scrap,	30,480	1·3	35,560	1·6	34,544	1·6
Yield,	...	102·0	...	100·1	...	99·2

Analyses of Pig-Irons suitable for Manufacture of Steel by the Bessemer and Open Hearth Processes.

Acid Processes.

Bessemer.

	Typical Analysis.	
Combined Carbon,	0·40	3·60
Graphite,	3·20	
Silicon,	2·25	
Sulphur,	0·05	
Phosphorus,	0·05	
Manganese,	0·50	
Arsenic,	0·03	

The Carbon will vary from 3·2 to 4·0 per cent. Silicon should not be less than 2·0, nor exceed 2·5 per cent. for Bessemer work in this country, although 3·0 per cent. Silicon pig-iron is sometimes used. In America and Sweden pig-iron containing 1·00 per cent. is frequently employed. The Phosphorus, Sulphur, and Arsenic should be as low as possible, but should never exceed 0·06 per cent. in each case. Manganese should not exceed 1·00 per cent.

Open Hearth or Siemens.

	Typical Analysis.	
Combined Carbon,	0·40	3·60
Graphite,	3·20	
Silicon,	2·00	
Sulphur,	0·04	
Phosphorus,	0·04	
Manganese,	0·60	
Arsenic,	0·03	

The Carbon will vary from 3·2 to 4·0 per cent. Silicon should not exceed 2·50, but may be as low as 1·00 per cent., and large quantities of Swedish pig-iron with this percentage of Silicon are used in Siemens furnaces in this country. Manganese should not exceed 1·00 per cent. Phosphorus, Sulphur, and Arsenic should be as low as possible, the lower the better, but should not exceed 0·05 per cent. in each case.

Basic Processes.

Bessemer.

	Typical Analysis.	
Combined Carbon,	3·40	3·60
Graphite,	0·20	
Silicon,	1·00 or less	
Sulphur,	0·05	
Phosphorus,	3·00	
Manganese,	2·00	
Arsenic,	0·03	

Pig-iron much higher than 1 per cent. Silicon can be used, and frequently is, but it is desirable to keep this as low as possible. The Phosphorus may be as low as 2·5 or as high as 3·5 per cent., but 3·0 per cent. gives better results. Sulphur and Arsenic the lower the better, and in no case exceeding 0·06 per cent.

Open Hearth or Siemens.

	Typical Analysis.	
Combined Carbon,	3·40	3·60
Graphite,	0·20	
Silicon,	1·00 or less	
Sulphur,	0·05	
Phosphorus,	2·00 or less	
Manganese,	2·00	
Arsenic,	0·03	

Pig-iron higher than 1 per cent. Silicon can be used, but it is desirable to keep this as low as possible. For rapid work and production of high-class material the lower the Phosphorus the better, although large quantities of steel are made from pig-iron with 3·00 per cent. or over of Phosphorus. The best all-round results, however, for general work are obtained with 1·75 to 2·00 per cent. Manganese is by no means necessary, but it is difficult to get basic pig low in Sulphur without high Manganese; provided Sulphur is low, 1·00 Manganese or even less is sufficient.

Typical Analyses of Steels from Bessemer and Open Hearth Processes.

Acid.

Bessemer.			Open Hearth or Siemens.		
	Soft Steel.	Rail Steel.		Soft Steel.	Medium and Hard Steel.
Combined Carbon, .	0·10 to ·15	0·32 to ·55	Combined Carbon, .	0·12 to ·20	0·20 to 1·50
Silicon, . .	0·02 ,, ·06	0·04 ,, ·08	Silicon, . .	0·04 ,, ·08	0·04 ,, ·35
Sulphur, . .	0·03 ,, ·08	0·05 ,, ·08	Sulphur, . .	0·02 ,, ·06	0·02 ,, ·06
Phosphorus,	0·04 ,, ·08	0·06 ,, ·08	Phosphorus,	0·02 ,, ·06	0·02 ,, ·06
Manganese, .	0·40 ,, ·80	0·60 ,, 1·00	Manganese, .	0·40 ,, ·60	0·40 ,, 1·00
Arsenic, . .	0·02 ,, ·06	0·02 ,, ·08	Arsenic, . .	0·02 ,, ·06	0·02 ,, ·06
Some special steels made from selected pig-iron will be as low as ·03 per cent. in Phosphorus and Sulphur.					

Basic.

Bessemer.			Open Hearth or Siemens.	
	Soft Steel.	Rail Steel.		Soft Steel.
Combined Carbon, .	0·08 to ·15	0·32 to ·55	Combined Carbon, .	0·10 to ·18
Silicon, . . .	trace.	trace ,, ·02	Silicon, . . .	trace
Sulphur, . .	0·03 to ·08	0·05 ,, ·08	Sulphur, . .	0·02 to ·06
Phosphorus, . .	0·04 ,, ·08	0·06 ,, ·08	Phosphorus, . .	0·03 ,, ·06
Manganese, . .	0·40 ,, ·80	0·60 ,, 1·00	Manganese, . .	0·40 ,, ·80
Arsenic, . . .	0·02 ,, ·06	0·02 ,, ·60	Arsenic, . . .	0 02 ,, ·06
The above are simply typical analyses taken from average steels, and it is not unusual to find the impurities exceed the higher limits given, and, on the other hand, for exceptional purposes steel is made with less than the minimum impurities given above.			High Carbon steel is rarely made in basic open hearth furnaces working with phosphoric pig-iron, and, if it is, is usually carburised to the required extent outside the furnace, by the Darby or some similar process. Exceptionally pure material containing little more than traces of Phosphorus is made in the basic Siemens by using special Hematite pig-iron.	

Analyses of Refractory Materials used for Bessemer Converters and Siemens Furnaces.

Acid or Silicious Materials.

Materials Suitable for Lining Converters.

Ganister.				Silica Bricks.				
	1.	2.	3.		1.	2.	3.	Made from Ganister. 4.
Silica, . .	92·05	94·60	95·20	Silica, . .	96·32	94·80	96·70	94·01
Alumina, .	2·70	1·40	0·59	Alumina, .	1·36	1·40	1·60	2·76
Oxide of iron,	1·85	0·90	0·74	Ferric Oxide,	1·20	1·10	0·65	0·55
Lime, . .	0·60	0·48	0·40	Ferrous Oxide,	nil	nil	nil	nil
Magnesia, .	0·20	0·16	0·16	Lime, . .	1·20	1·90	0·61	2·36
Alkalies, .	0·20	0·14	0·18	Magnesia, .	...	...	...	0·12
Water, .	2·00	2·60	2·70	Titanic Oxide,	...	0·60	...	...
				Alkalies, .	0·21	0·19	0·20	0·18
	99·60	100·28	99·97		100·29	99·99	99·76	99·98

When Silica bricks are used they are frequently jointed with fine ganister, or finely-ground Silica stone, similar in composition to any of the bricks given above.

Materials for Siemens Furnaces.—For the walls, ports, and roofs of Siemens furnaces any of the Silica bricks given above would be suitable as far as the analysis is concerned, all being sufficiently infusible, and they would be set in finely-ground Silica cement containing about 95 per cent. of Silica.

Other questions, however, than those of infusibility, such as contraction and expansion, are very important in determining the selection of a brick for any particular purpose. Thus, although the walls and roof of a Siemens furnace would be built of bricks of similar composition, the texture or fineness of structure of brick selected is often different, coarse-grained bricks being found to give the best results for roofs subject to considerable variation in temperature, and the consequent alternate contraction and expansion. One of the best known bricks used for furnace roofs is the Dinas brick made from the Dinas rock in South Wales. The rock is generally mixed with about 1 per cent. of lime to act as a binding material when made into bricks, which are usually coarse-grained, the rock being only coarsely ground before moulding. The following is a typical analysis:—

Silica, ...	96·80
Alumina, ...	0·92
Ferric Oxide, ...	0·50
Lime, ...	1·20
Alkalies, ...	0·20
	99·62

The Alkalies in all kinds of Silica bricks should be as low as possible, preferably not exceeding 0·5 per cent.

For the regenerators Stourbridge or similar fire-bricks are employed.

Basic Materials.

Dolomite.			Calcined Dolomite.			Magnesite.		Chrome Ore.	
	1.	2.		1.	2.				
Silica, .	1·10	0·90	Silica, .	3·66	2·50	Silica, .	0·92	Silica, .	2·25
Oxide of Iron and Alumina,	1·64	1·30	Oxide of Iron and Alumina,	4·80	3·99	Oxide of Iron and Alumina,	4·40	Ferrous Oxide,	35·82
								Alumina,	3·01
Lime, .	33·20	31·00	Lime, .	55·50	57·32	Lime, .	1·82	Lime, .	4·20
Magnesia,	19·60	20·60	Magnesia,	34·83	34·75	Magnesia,	42·70	Magnesia,	2·60
Carbonic Acid, .	44·30	46·34	Loss on ignition,	1·06	1·00	Carbonic Acid, .	50·01	Chromic Oxide,	51·54
	99·84	100·14		99·85	99·56		99·85		99·42

CHAPTER IX.

THE PRODUCTION OF STEEL CASTINGS.

The production of steel castings is so essentially one of those arts which can be acquired only by long experience, and involves a knowledge of so many little details which are of the greatest importance, that it is impossible to do more than give a very general description and draw attention to some of the more important points which are necessary to success.

In addition to preparing metal of the right composition and casting at the right temperature, two all-important points, the composition of the mould, the method of moulding, disposition of the feeding heads, and means of overcoming excessive local strains in contraction, have all to be anticipated and met to secure a satisfactory result. When it is remembered that many of these points vary with different castings according to their weight, strength required, their complexity or the reverse, it will be seen how impossible it is to lay down any very definite rules, and that each case must be left largely to the judgment of the individual responsible.

Steel Employed.—Castings are made from open hearth furnaces, both acid and basic, but generally the former, and from small tipping converters like the Robert, Walrand, and others, or from crucibles, and excellent results can be obtained with all these processes; the electric furnace is also being used with very good results. For the general purposes of a steel foundry when castings of varying sizes are required, a small open hearth furnace is found to give the best results for all-round work, as greater control over both the composition and casting temperature can be exercised. The essential thing in all steel castings is to obtain solid castings free from blowholes, and for this purpose it is most important to get a "dead melt"—that is to say, to finish with a good, thick, clean, non-oxidising slag. If the finishing slag contains much free Oxide the metal will be over-oxidised, with the result that the casting will be spongy. The slag must at the same time be fluid, so that it does not get entangled with the metal, and carried into the casting, and so cause serious defects, and a little ground Fluorspar added to the metal in the ladle is found to give good results in clearing the metal. The temperature of casting is a most important matter, and will vary to some extent

with the size of the casting, hotter metal being necessary for small intricate castings than for large, heavy, thick ones. On the one hand, the metal must not be too hot, or this will cause piping and unsoundness, owing to large and unequal contraction; and, on the other hand, if the temperature be too low, the surfaces of the castings will be defective, and there is a danger of the moulds not filling completely, owing to insufficient fluidity. Experience has shown that, provided the metal be sufficiently fluid, it is better to keep the temperature too low rather than too high, and this is one reason why Aluminium gives such good results in steel castings, as by removing Oxides and so facilitating the flow of metal from the ladle, it enables the steel to be cast at a slightly lower temperature and at the same time insures a good surface on the castings.

It is desirable always to retain a little Silicon and also some Manganese in the bath of metal to prevent over-oxidation, and a little Silico-spiegel and Silicon pig added towards the end of the operation, when the greater part of the impurities have been removed, are beneficial; this addition of Silico-spiegel or Silicon pig tends also to insure sound castings, although it is not so largely used as it was before the introduction of Aluminium, which has, to some extent, replaced it.

The exact way in which Silicon and Manganese act is not thoroughly understood, but there is little doubt considerable portions of the Silicon and Manganese are oxidised to Silica and Oxide of Manganese by some of the oxidising gases present, and, by removing these gases, prevent blowholes. This, however, is only a partial explanation. The action of Aluminium is undoubtedly a reducing one, and the increased fluidity of the metal is in all probability due to the removal of Oxides of Iron. There are strong reasons for believing that Silicon, Manganese, and Aluminium also increase the solvent power of the steel for gases, and thus prevent the dissolved gases being liberated on the steel cooling.

It is important that neither too much Silicon nor Manganese should be added, as the finished casting generally should not contain more than 0·25 per cent. Silicon and about 0·8 per cent. Manganese, and in no case should it exceed 0·55 and 1·2 per cent. respectively.

Aluminium, too, must be added cautiously, especially when making high Carbon castings, as a very small quantity, a few ounces to the ton of metal, is all that is required to produce soundness, and if added in too large quantities, especially to high Carbon steel, it seems to have the curious effect of causing irregular segregation of impurities in the metal, and piping of the ingots. The influence of large quantities of Aluminium on high Carbon steel is a very important question, which has never been completely investigated.

The percentage of Carbon in steel for castings will vary within wide limits from 0·20 to 0·80, or 0·90 per cent., but the great bulk of steel castings contain less than 0·50 per cent. of Carbon, probably about 0·35 per cent.

Phosphorus and Sulphur, although probably not quite so harmful as in structural material, should not exceed 0·06 per cent. each, or, at the outside, 0·08 per cent., and there should be no difficulty in working to these limits, as it simply means selecting high-class pig-iron and scrap. If Sulphur be present to any extent, the castings are very liable to tear during cooling in the moulds, and wasters greatly increase. The proportion of scrap and pig in a casting charge will vary with the grade of steel required, but within reasonable limits any amount of scrap can be used, and in some cases as much as 80 per cent. of the charge, when no ore is added. In most steel foundries the scrap from heads, gits, and wasters is sufficient for the require-

ments, and is much to be preferred to using outside scrap of more or less unknown composition, although when heavy scrap charges are regularly employed, the foundry scrap will usually have to be supplemented from outside sources. The following table gives a few typical analyses of some steel castings, with the maximum stress, elongation, and reduction of area :—

TABLE LIV.—Steel Castings.

Description of Casting.	Carbon.	Silicon.	Manganese.	Sulphur and Phosphorus.	Maximum Stress per sq. in.		Elongation per cent. on 2 inches.	Bend Test.
					Tons.	Lbs.		Degrees.
Rudder frame, .	0·16	0·49	0·576	Below ·06 per cent. in all cases.	29·6	66,300	37	90 *a.b.*
Shaft bracket, .	0·21	0·53	0·630		33·8	75,800	23	80 *a.b.*
Eccentric-rod, .	0·20	0·361	...		29·6	66,300	24	120 *a.b.*
Pivot plate, .	0·40	0·326	...		39·2	87,980	24	85
Casting, . . .	0·47	0 501	...		42·0	94,100	14	40
Roller path, .	0·33	0·501	...		41·0	92,000	18	64
,, .	0·22	0·42	0·594		30·3	67,900	29	100 *a.b.*

a.b. signifies that the test pieces bent over to the given angle *without* fracture ; in other cases the sample broke or cracked at the angle indicated.

Description of Moulds.—The preparation of the moulds is a most important factor in the manufacture of good castings, and they are divided into two classes, known as "green sand" and "dry sand," the former being generally used for the lighter castings, and the latter for medium and heavier castings.

"Green Sand" Moulds.—This is a generic term for moulds which are not "baked" or dried previously to receiving the molten steel. They are usually made for the lighter class of castings requiring little finish or smooth surface, such as cast steel wheels for colliery waggons, pedestals or "bearings," barrow wheels, &c. The sand of which these moulds are made is ordinary foundry floor sand, which has been strengthened by an addition of a loam sand, and passed through a mixing and grinding mill. Sometimes a small proportion of coal dust is incorporated with this sand, and in "working up" this sand for certain work, small quantities of either beer-dregs or molasses are added. As, however, the sand is "worked" or made up according as the class of work to be moulded varies, there can be no hard and fast rule laid down, and most foundry foremen have their own ideas as to the best mixture for any particular work.

The composition of the added loam sand approximates to the following analyses :—

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO
92·50 per cent.	4·56 per cent.	2·14 per cent.	0·60 per cent.	0·32 per cent.

Green sand moulds are made either by hand ramming or machine moulding, and where repetition work for large quantities of castings is required, the latter process, of course, shows considerable economy in cost of production over the former, and invariably better work is produced, as the sand is more evenly and regularly consolidated round the pattern, and the machine admits of a true "draw" of pattern from the sand, thus ensuring a cleaner and "sharper" definition in the mould.

In addition to the mould proper, the "cores" are of great importance ; these, of course, are the various shaped pieces or blocks of sand which are laid in the moulds to "cut out" or displace metal, as in the case of the hole in

a wheel boss. These are usually made of sand similar to the mould, and must be "vented" to allow of the free escape of gas from the mould to the outside when casting. These cores are invariably dried or baked, even for green sand moulds. After the pattern is drawn from a "green sand" mould, and the mould "cored," it is ready to receive the metal—that is to say, no "paint" or black-lead is put on the surface of this class of mould, as in the case of "dry sand" moulds.

"Dry Sand" Moulds.—This is a term given to moulds usually made of sand with a more or less thick facing of moulders' "facing composition," and used for a heavier and more important class of castings where it is desirable to have a smooth, clean "skin" or surface.

The following analysis represents a steel moulding composition for this class of work :—

Loss on calcination	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O
4·84 per cent.	59·81	25·16	5·42	1·14	0·75	3·00 = 100·12	

This composition may be made up by grinding and mixing together ganister stone, silica bricks, fire-bricks, old plumbago crucibles, and small quantities of coke.

In preparing the mould a layer of sand is spread out on the bottom of the "box," and carefully smoothed over. This is then covered with a layer of moulders' "composition," varying according to the size of the casting, to, say, $\frac{1}{2}$-inch or more in depth. On this the pattern is now placed, and a layer of "composition" spread over it, sand sifted over this, and the whole rammed to the pattern. The pattern is then withdrawn from the mould, both of them being always made in two or more pieces, and the face of the latter is coated with black lead wash, Silica paint, or with a mixture of both. The moulds are then "stoved"—*i.e.*, placed in drying stoves—where they are heated *very gradually*, otherwise they are liable to split or crack owing to the too rapid escape of steam or to the too sudden expansion of the mass of sand. The time necessary for drying any particular mould must depend upon its size, thickness, and shape; but it is of the greatest importance to make quite sure that the mould is absolutely dry before the metal is run into it, otherwise serious defects will probably appear in the casting, and there is also a danger of accidents from the metal being blown out of the mould by a sudden generation of steam.

On removing the dried mould from the stove, it is usual to coat the surface with coal tar or black lead, and either to put it back in the stove for a short time or to rely upon the initial heat of the hot mould to dry this coating.

The "venting" of moulds and cores, the disposition and sizes of the feeding heads, the position of the runners, the anticipating and dealing with contraction, local strains, &c., &c., are all points of the greatest importance, to which in steel foundry practice attention has to be given to a considerably greater extent than in iron foundry work.

Internal Stresses in Castings.—One of the greatest difficulties the steel founder has to overcome is that of fracture of the casting, due to "shrinkage" or internal stresses caused by contraction of the metal in passing from the liquid to the solid state during cooling down.

Steel founders have endeavoured to overcome this trouble in a variety of ways, such as liberating the sand of the mould from some parts of the casting as soon after pouring as possible, removing the core so as to allow of free contraction, comparatively quick cooling of the heavy parts in relation to the lighter parts, and also by a system of "tying" thick and thin parts of the casting by either brackets of metal or "dogs"—*i.e.*, bent iron bars

cast in locally to form ties. The amount of shrinkage varies with the composition and heat of the metal; the softer and hotter the metal the greater is the shrinkage; but as smoother castings are obtained from hot metal, it is better in many cases, where this is of special importance, to cast hot and allow for shrinkage.

Shrinkage varies from 1·5 to 1·8 per cent. or even 2 per cent., according to the composition and heat of the metal—say, equal to about $\frac{3}{16}$ inch to the foot.

Annealing the Castings.—Castings of very hard steel have a tendency to crack (or "fly") when cooling; but this tendency can to a great extent be counteracted by efficient annealing, which removes, or, to a great extent, reduces, the initial stresses set up in the metal while passing from the liquid to the solid state in the mould, and thus toughens the casting. The regular and gradual heating of castings during annealing, and the temperature of annealing, are very important questions which are now receiving considerable attention at the hands of steel founders; and in many works, especially where very large and costly castings are made, recording pyrometers are attached to the furnaces, so that any irregularity in the working of the furnace, whether from negligence on the part of the workmen or other causes, is at once discovered. The temperature usually employed is about 900° C. for low Carbon castings, and somewhat less (about 800° to 850°) for castings containing above ·50 per cent. Carbon; but the annealing temperature which produces the greatest strength, combined with ductility, in castings containing different percentages of Carbon, has not been fully threshed out, and is being investigated by several metallurgists. In a paper "On the Properties of Steel Castings," read before the Iron and Steel Inst., Prof. Arnold* gives the results of heating his experimental bars of pure Carbon steels for 70 hours at a temperature of 950° C., with slow cooling for another 100 hours, this temperature being selected because Prof. Arnold has found it is frequently reached in works' practice. The results are given in Table lv., and are of interest as forming the basis for a complete series of researches, but are not comparable with results obtained from commercial steels.

The time of heating and of cooling will largely vary with the weight and the shape of the casting, and one great difficulty in annealing castings is to anneal the different parts equally, as sometimes it takes many hours to heat the body of the casting through, and all this time the lighter parts are exposed to a long soaking.

The general effect of annealing castings is similar, only more marked, to that produced on annealing rolled or forged steel—viz., a removal of internal stresses, accompanied with increase in elongation and contraction of area, and decrease in maximum stress; in other words, the casting is toughened. Unannealed castings are nearly always more or less brittle when subjected to shock, and annealing very largely removes this brittleness.

The few examples in Table lvi. show the effect of annealing and also of oil tempering on castings or forgings containing different percentages of Carbon, and may be taken as fairly representative.

* *Iron and Steel Inst. Journ.*, 1901, vol. i.

TABLE LV.—Prof. Arnold's Results on Annealing Small Iron and Carbon Castings moulded in Dry Composition

Mark.	Process.	Analysis.						Specific Gravity.	Tensile.				Bending $\frac{3}{4}$-inch Radius.	Compression per cent. at 100 Tons per sq. in.	Remarks.
		CC.	Si.	Mn.	S.	P.	Al.		Elastic Limit. Tons per sq. in.	Maximum Stress. Tons per sq. in.	Elongation per cent. on 2 ins.	Reduced Area. Per cent.			
FeB	Crucible	0·07	·023	·05	·02	·01	·018	7·9162	10·69	19·79	30·0	38·7	180° U	62·3	As cast
		0·07						7·9249	9·10	19·18	46·0	65·1	180° U	63·0	Annealed
473	,,	0·06	·06	·07	·02	·02	not estimated	7·9954	11·53	17·48	18·5	28·5	180° U	62·7	As cast
		0·06						7·9247	8·83	16·91	18·5	30·9	180° U	64·4	Annealed
521	,,	0·18	·01	·09	·027	·01	·023	7·8868	11·85	19·92	19·5	29·1	180° U	61·8	As cast
		0·16						8·0141	9·35	19·51	31·0	47·0	180° U	61·9	Annealed
458	,,	0·37	·05	·08	·03	·02	·02	7·9164	14·71	21·77	5·0	5·9	40°	55·5	As cast
		0·37						7·9761	10·28	20·84	12·5	19·8	180° U	58·9	Annealed
518	,,	0·37	·04	·10	·023	·017	·025	7·9842	15·95	23·22	6·0	6·3	32°	56·2	As cast
		0·37						8·0925	9·00	21·97	20·0	22·4	180° U	57·7	Annealed
CC	,,	0·42	·04	·06	0·2	·01	not estimated	7·8510	17·22	23·41	6·5	8·4	90°	45·7	As cast
		0·40						7·8653	10·08	24·03	24·5	29·0	180° U	50·0	Annealed
541	,,	0·44	·076	·03	0·3	·016	·032	7·9560	13·33	24·62	8·4	12·3	43°	57·3	As cast
		0·35						7·9782	12·21	23·50	14·0	16·0	180° U	62·3	Annealed
CC2	,,	0·48	·09	·10	0·2	·02	·022	7·8937	18·38	18·38	3·0	3·2	12°	52·3	As cast
		0·50						7·9607	15·21	26·75	20·5	15·7	86°	56·3	Annealed
YB	,,	0·50	·075	·07	·022	not estimated.	not estimated	8·0449	17·53	19·28	2·5	1·7	12°	50·8	As cast
		0·54						8·0054	10·52	25·28	16·0	18·4	180° U	55·5	Annealed

Mark.	Process.	Analysis.						Specific Gravity.	Tensile.				Bending ½-inch Radius.	Compression per cent. at 100 Tons per sq. in.	Remarks.
		cc.	Si.	Mn.	S.	P.	Al.		Elastic Limit. Tons per sq. in.	Maximum Stress. Tons per sq. in.	Elongation per cent. on 2 ins.	Reduced Area. Per cent.			
517	Crucible	0·56	·08	·08	·031	·019	·037	7·8981	15·74	22·98	3·0	3·5	23°	48·6	As cast
		0·50						7·9644	12·32	25·32	10·0	10·0	135°	53·3	Annealed
556	,,	0·60	·073	·07	·031	·018	·028	7·9276	16·92	18·80	1·5	1·8	13°	51·0	As cast
		0·60						7·9533	9·80	16·49	2·0	2·4	33°	55·0	Annealed
601	,,	0·70	·11	·10	·045	not estimated	·050	7·8954	18·52	20·12	1·5	1·8	5°	47·2	As cast
		0·72						7·8612	13·92	30·32	6·0	5·3	30°	51·3	Annealed
459	,,	0·86	·06	·05	·02	·02	·018	7·9468	26·48	26·48	1·5	2·1	0°	broke at 54 tons per sq. in.	As cast
		0·80						7·9580	15·48	23·76	2·5	4·2	18°	45·4	Annealed
524	,,	0·97	·058	·03	·025	·018	·030	7·9054	22·25	32·42	2·0	1·8	8°	sheared at 90·4 tons per sq. in.	As cast
		0·83						7·9600	18·54	29·03	4·0	1·7	50°	50·7	Annealed
460	,,	1·29	·098	·28	·02	·02	·042	7·8788	22·30	22·30	0·0	0·0	0°	33·1	As cast
		1·10						7·8536	16·55	29·93	2·5	3·5	20°	40·7	Annealed
522	,,	1·95	·034	·02	·015	·016	·031	7·8454	13·18	13·18	0·0	0·0	0°	broke at 99·5 tons per sq. in.	As cast
		1·10						7·8771	12·86	12·86	0·0	0·0	3°	58·5	Annealed
573	,,	1·76	·058	·07	·020	·022	·020	7·7424	20·32	20·32	0·0	0·0	0°	17·3	As cast
		1·38						7·7661	11·69	14·11	0·0	0·0	5°	52·7 sheared	Annealed

TABLE LVI.—Effect of Annealing.

Carbon.	Unannealed.			Annealed.		
	Tensile Strength or Maximum Stress per sq. inch.		Elongation per cent. on 2 inches.	Tensile Strength or Maximum Stress.		Elongation per cent. on 2 inches.
Per cent.	Tons.	Lbs.		Tons.	Lbs.	
·23	30·68	68,780	22·40	30·00	67,220	31·40
·37	38·18	85,300	8·20	36·70	82,220	21·80
·53	40·23	90,100	2·35	47·50*	160,480	9·80

Carbon.	Silicon.	Manganese.	Unannealed.				Annealed.			
			Tensile Strength per sq. in.		Elongation per cent. on 2 inches.	Reduction of Area.	Tensile Strength per sq. in.		Elongation per cent. on 2 ins.	Reduction of Area.
Per cent.	Per cent.	Per cent.	Tons.	Lbs.		Per cent.	Tons.	Lbs.		Per cent.
0·30	0·22	0·63	33·6	75,220	16	26·8	31·0	69,500	24	43 8
0·50	0·40	0·66	44·4	99,500	2	4·13	44·0	99,520	12	16·8

The following figures show the effects of "annealing" and "hardening" and "tempering":—

C.	Si.	Mn.	S.	P.	Fe.	Annealed.					Hardened and Tempered.				
						Tensile Strength per sq. in.		Elastic Limit per sq. in.		Elongation per cent. on 2 ins.	Tensile Strength per sq. in.		Elastic Limit per sq. in.		Elongation per cent. on 2 ins.
Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Tons.	Lbs.	Tons.	Lbs.		Tons.	Lbs.	Tons.	Lbs.	
·35	·023	·252	·019	·038	99·35	34·4	77,080	17·6	39,500	27	48·9	109,560	29·06	65,090	16·5
·43	·028	·216	·023	trace	99·30	34·9	78,180	19·26	43,100	25·5	49·6	111,100	31·1	69,700	17·0

The first five results were obtained on castings and the last two on samples taken from a forged gun-jacket, hardened by quenching in oil at about 820° and re-heated to 650°. Annealing, especially in the case of high Carbon castings, does not seem to appreciably lower the maximum strength, although it decreases the elastic limit, and it largely increases both the elongation and the reduction of area.

* This is an abnormal result, although a slight increase in the maximum stress on annealing is not very uncommon.

CHAPTER X.

THE PRODUCTION OF SHEAR AND CRUCIBLE STEEL.

The Cementation Process.—Notwithstanding the immense development, in recent years, of the Bessemer and Siemens processes, special varieties of high Carbon steel continue to be made from what are known as 'cement bars," by the converting or cementation process, which has so long been practised in the Sheffield district, and according as these carburised bars are piled and welded together, or fused in crucibles and cast into moulds, they are respectively known as shear or crucible cast steel.

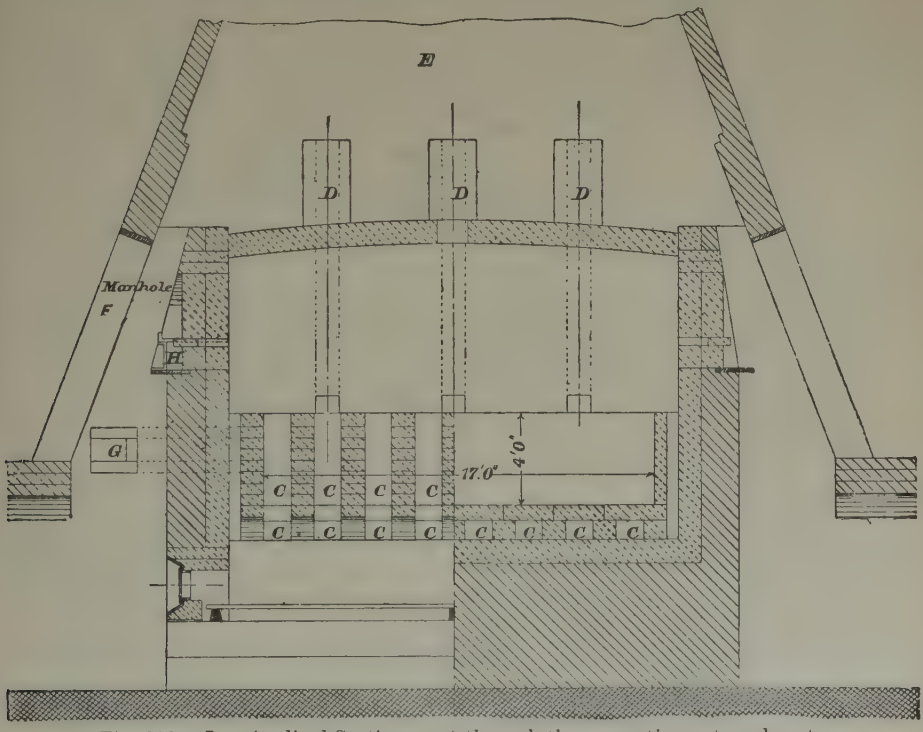


Fig. 183.—Longitudinal Section, part through the converting pot, and part through the flue.

The cementation process depends upon the well-known fact that iron, when heated with exclusion of air in contact with Carbon, absorbs that element in varying proportions which depend upon the time the operation lasts, and the temperature at which it is conducted.

Figs. 183 and 184 give transverse and longitudinal sections of an ordinary cementation furnace, in which wrought-iron bars are heated, in contact with Carbon, for varying periods according to the degree of carburisation required.

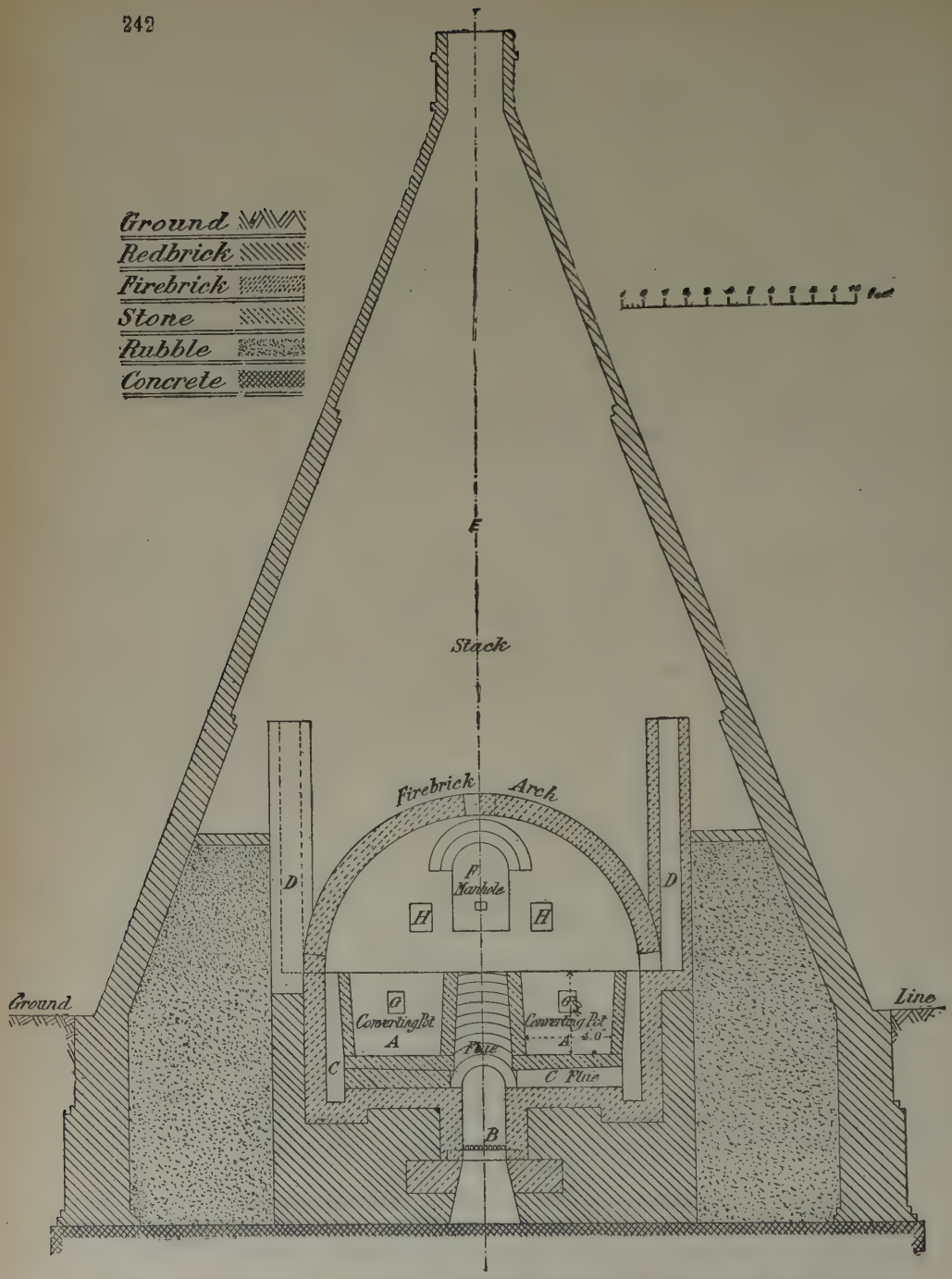


Fig. 184.—Transverse Section of Cementation Converting Furnace—A, Converting pots; B, firegrate; C, flues for distributing heat; D, short chimneys communicating with stack; E, conical hood or stack; F, manhole for introducing or withdrawing charge; G, holes for removal of trial bars; H, charging holes.

The converting pots, which form a part of the furnace, consist of two rectangular fire-brick or stone chambers, with fire-bars underneath, running the entire length of the pots, and the equal distribution of heat is effected by means of flues shown in the drawing. The size of the pots varies from 8 to 15 feet in length, and from $2\frac{1}{2}$ to 4 feet in width, and they are generally about 3 feet deep, with a capacity of from 8 to 13 tons of bars. A manhole, which is bricked up during the converting, is provided at the end of the furnace for charging and withdrawing the bars. There is a hole at one end of each pot, and a corresponding hole is left in the furnace for the insertion and removal of trial bars, which are withdrawn from time to time, and examined to see how the carburisation is proceeding.

The highest quality of cement bars is made from best Swedish iron, manufactured by the Walloon process. These are hammered bars, about $2\frac{1}{2}$ to 3 inches wide, and $\frac{5}{8}$ to $\frac{3}{4}$ inches thick, and are generally about 12 feet long, and the (L) iron, made from purest Dannemora iron ore, is probably the brand which has the highest reputation for producing the finest qualities of steel. Numerous attempts have been made to use bars of exceptionally pure material, such as steel made from hematite in a basic Siemens furnace, and other extremely pure varieties of both iron and steel, but according to the experience of Sheffield steel makers an inferior product is always the result. This is certainly very difficult to explain, as, so far as chemical composition and purity of material go, the materials tried have, in many cases, been distinctly better than even the best Walloon iron.

Some allowance must no doubt be made for Sheffield manufacturers viewing with prejudice the results obtained by a departure from long recognised practice, but prejudice would hardly be strong enough to induce them, provided the comparatively low-priced English material gave equally good results, to pay many more pounds per ton for Walloon iron. This seems to prove that they have very good reasons for continuing to use Swedish iron, and that for some cause as yet unexplained, the Swedish iron produces a higher class product than cheaper materials of apparently better chemical composition.

Another point which requires explanation is that hammered bars are preferred to rolled bars for the best qualities of steel, and are said to give a better class of finished material. The process of cementation is conducted as follows :—The bottoms of the pots are first covered with a layer of charcoal on which the bars are laid on their flat sides, separated from each other by about half an inch of charcoal, then another layer of charcoal is placed on these and another layer of bars, these alternate layers of bars and charcoal being repeated until the pots are full, when the whole is covered with a final layer of charcoal. The top of the pot is then closed by an arch made of wheel swarf—*i.e.*, a mixture of silicious particles and partially rusted steel, obtained from the grindstones in cutlery grinding—which at the heat of the furnace frits together, and forms a practically airtight lute. The charcoal, prepared from the harder woods, is usually preferred, but this is not essential, and, according to Bauerman, birch is used in Sweden, beech in Rhenish Prussia, and oak in England. Before use, the charcoal is passed through a $\frac{1}{2}$ or $\frac{3}{4}$ inch mesh.

When the furnace is charged the manhole is bricked up, all small openings tightly luted with clay, the fire lighted, and the temperature of the furnace raised gradually to a red heat, which usually takes about twenty-four hours. After about two or three days the furnace will reach its full temperature, and this is maintained for a period of from 7 to 11 days, according

to the grade of steel required. For so-called mild heats the furnace is fired for 7 to 8 days; for medium heats about 9½, and for very high Carbon heats about 11 days. At the end of this time the fire is banked up, and the whole furnace allowed to cool down for a period of about 14 days.

The bars when removed from the cementation furnace are covered with surface blisters, and are known as "blister bars," or "blister steel." These blisters should be small and equally distributed over the bar, and should not run along special lines.

Grades of Cement Bars.—Cemented bars are generally classed in seven grades, according to the percentage of Carbon they contain, and are numbered from 1 to 6, grade 7 being called "doubly converted bars." They are broken and graded according to fracture. Sometimes, owing to the carelessness of the workmen, or to defects in the furnace, the pots become too highly heated, with the result that the surface of the bars is slightly fused, and these are known as "glazed bars." If by any chance the pots should crack, or any of the fireclay lutes give way so that air gains access, the bars are liable to become oxidised, and are then known as "aired bars." The greatest skill is shown by experienced men in sorting these bars, and they are able to detect very slight variations in the Carbon contents.

Micro-structure of Cement Bars.—Very mild bars contain an unaltered central core of mild steel known as "sap," and very hard bars are easily distinguished by being what is known as "flaked," as, on fracture, they present bright cleavage planes, which are due, according to Professor Arnold, to the fracture taking place along the junctions of the cementite or Fe_3C walls, enveloping the crystalline grains of pearlite or true steel. Professor Arnold,* in a very exhaustive paper on the "Micro-chemistry of Cementation," gives a series of analyses of cemented bars, showing the variation of the Carbon from the outside to the centre of the bars, and also illustrates the same point by a beautiful series of coloured micrographs.

The iron used in the experiments was Swedish-Lancashire hearth bar iron, made from Dannemora pig and branded "Little S," and had the following composition, which may be taken as typical of Swedish bar iron:—

Carbon,	0·050
Silicon,	0·037
Sulphur,	0·006
Phosphorus,	0·012
Manganese,	0·108
Copper,	trace
Arsenic,	0·007

The carbon in cement bar varies considerably from the outside to the centre, but the following were the *mean* Carbon contents of the bars after cementation :—

Material.	Mean Carbon.	Remarks.
	Percentage.	
No. 2 bar,	0·45	Carbon in three distinct layers.
No. 3 bar,	1·13	,, ,,
No. 4 bar,	1·33	Carbon in two distinct layers.
No. 5 bar,	1·60	Practically uniform.
No. 6 bar,	1·80	,, ,,
Doubly converted aired bar,	1·90	Fairly uniform.
No. 4 bar (after airing),	1·04	...

* *Iron and Steel Inst. Journ.*, 1898, vol. ii., p. 185.

No. 2 bar in these experiments is said to have been somewhat milder, and No. 3 somewhat harder than the average Nos. 2 and 3. Cuttings were taken from the outside of bars Nos. 2, 3, and 4, to the centre, at varying depths, increasing in the case of No. 2 by ·02 of an inch, and in the case of Nos. 3 and 4 by ·04 of an inch, and the analyses of these are given in Table lvii., and show very clearly the gradual penetration of Carbon into the bars.

TABLE LVII.

Cut No.	Depth into Bar in inches.	Mean Carbon per cent.			
		No. 2 Bar.	No. 3 Bar.	No. 4 Bar.	No. 4 Bar (aired).
1 (outside), . . .	0·02	0·98	...	...	0·00
2, ...	0·04	0·95	1·40	1·50	0·00
3, ...	0·06	0·76	...	...	0·30
4, ...	0·08	0·63	1·26	1·45	1·20
5, ...	0·10	0·50	...	...	1·45
6 (median), . . .	0·12	0·39	1·15	1·27	1·45
7, ...	0·14	0·37	...	...	1·45
8, ...	0·16	0·31	1·10	1·29	1·40
9, ...	0·18	0·18	...	...	1·38
10, ...	0·20	0·15	0·98	1·29	1·38
11, ...	0·22	0·10	...	...	1·35
12 (centre), . . .	0·24	0·10	0·88	1·15	1·16
Mean carbon in half the bar, ...	...	0·45	1·13	1·33	1·04

Aired Bars.—If, as already pointed out, air gains access, by any means, to the bars during conversion or cooling, and the surface becomes more or less oxidised, such bars are known as "aired bars." An analysis of a No. 4 bar in layers of ·02 of an inch thick, from outside to centre, is given for comparison with the normal No. 4 bar, and it will be seen how the Carbon has been entirely removed from the surface of the bars. The analytical results in Table xxxix. are fully confirmed by the micro-photographs, for which the student must be referred to the original paper. Bars Nos. 5 and 6 show no difference in Carbon percentages between the outside and centre, being practically uniform throughout. Double converted bars, which sometimes contain slightly over 2 per cent. of Carbon, are obtained by two conversions, but Professor Arnold says that, so far as his experience goes, he has not found it possible to introduce much over 2 per cent. by cementation even after ten conversions.

In Sheffield the six grades of steel referred to have received, for convenience, the names given below, and, according to Mr. Seebohm,* contain about the following percentage of Carbon :—

1. Spring heat, ...	0·50 per cent.
2. Country heat, ...	0·63 ,,
3. Single shear heat, ...	0·75 ,,
4. Double shear heat, ...	1·00 ,,
5. Steel through heat, ...	1·25 ,,
6. Melting heat, ...	1·50 ,,

These percentages of Carbon are somewhat lower than those found by Professor Arnold in the bars he examined, but probably different makers

* *Iron and Steel Inst. Journ.*, 1884, p. 372.

have slightly different ideas as to the exact percentage of Carbon it is advisable to put in the various grades.

The Origin of the Blisters.—The cause of the production of the blisters on the surface of converted steel has in time past led to much discussion, but was finally settled by Dr. Percy, who, writing in 1864, suggested that they were due to the action of Carbon on the intermingled slag in the bars of iron used. This slag consists of ferrous silicate with more or less Oxide of Iron, and the result of the action of Carbon is the production of Carbon Monoxide in the interior of the bar, which, being at a high temperature, would be soft and readily expanded by the gas so produced. When the suggestion was made there was no experimental evidence of its correctness, but this Dr. Percy was afterwards able to supply,* and to prove that when iron which has been remelted, and so freed from intermingled slag, is subjected to the cementation process, no such blisters are produced, although in other respects the metal is converted as usual. Sir W. Siemens, in discussing the above results,† also stated that he had invariably found that when mild steel is subjected to cementation no blisters are produced, although hard steel is obtained as usual.

The Diffusion of the Carbon.—The actual way in which the diffusion of Carbon through the metal takes place, whether diffusing as Carbon in the same manner as a solid gradually diffuses when dissolved in a solvent, or whether as Carbides of Iron, is still a matter which is open to discussion, and much has been written in support of both views. As bearing on this question the experiments of Messrs. Metcalf and Langley may be cited, which clearly showed that Carbon is able to readily travel about in steel bars at high temperatures, although they did not throw much light upon the question whether they diffused as a Carbide or as Carbon. In these experiments a bar of high Carbon steel was placed in the centre of a mould, and mild steel was poured around it; the compound piece was then rolled down into a square bar. In a transverse section of the compound bar resulting, the hard interior strip could be plainly distinguished both by the difference in the action of the cutting tool upon it, and by etching with nitric acid. The outline of this hard centre was carefully marked off by means of a centre punch with holes rather less than $\frac{1}{16}$ of an inch in depth. The piece was then closely wrapped in a sheet-iron covering and exposed to a heat somewhat below the melting point of copper for five hours; it was then cooled and the metal planed down nearly to the bottom of the punch marks. The Carbon was then found to have travelled outwards from the hard interior, and to have formed a nebulous fringe in the softer steel. A similar observation had been previously made by Sir F. Abel, who annealed some thin steel discs containing about 1 per cent. of Carbon in a closed cast-iron box between two wrought-iron plates for about 24 hours. On afterwards analysing the discs it was found that the Carbon was reduced to 0·1 per cent., thus showing that this element had to a great extent passed out of the steel and been absorbed by the wrought iron.‡ Experiments by Mr. G. P. Royston also showed that if steel and wrought-iron plates were placed in close contact, the wrought iron gained in weight and the steel lost, and this gain in the wrought iron corresponded almost exactly with the loss of weight of Carbon in the steel when the plates were heated *in vacuo*. These facts have been generally confirmed by a very systematic series of experiments conducted by Messrs. Arnold & McWilliam§ on the diffusion of elements through steel at different temperatures. Cylinders of pure iron, bored with

* *Iron and Steel Inst. Journ.*, 1878, vol. i., p. 116. † *Ibid.*, p. 122.
‡ *Trans. Inst. M.E.*, 1883, p. 57.
§ *Iron and Steel Inst. Journ.*, 1899, vol. i.

the greatest care, were shrunk on to high Carbon steel cores and heated *in vacuo* for ten hours at a temperature of 1,000° C., when very considerable diffusion was found to have taken place, the Carbon having increased from ·05 to ·50 in one case in the outside jacket. In a further series of experiments it was shown that no diffusion took place from high Carbon cores with 1·78 per cent. C. to the low Carbon jacket during six hours below 740° C., but that it became just perceptible at 785° C., and that at 855° the diffusion took place readily. When, however, the Carbon in the outside jacket was increased to ·89 per cent., the diffusion from the internal core to external jacket did not apparently take place until a higher temperature was reached—viz., 960° C. Although these results and others given in the paper are of the greatest interest, they do not settle the question of the manner of diffusion of the Carbon, and further data are required before this point can be fully and profitably discussed. These facts, however, seem to indicate that, as Professor Arnold says, it would be possible to convert iron up to ·90 per cent. Carbon at a temperature of about 800° C., but that to produce bars with higher percentages of Carbon a temperature of at least 950° C. is required. In practice, the actual temperature is about 1,000° C., and according to Bauerman, who has studied the process very carefully in all countries where it is in use, the action is much more rapid at about 1,100° C., or just above the melting point of copper.

Spring Steel.—The blister bars, after conversion and separation into the various grades, are drawn out under the hammer or rolled at a yellow heat, and are then known as "plated bars" or "bar steel." Formerly springs were almost entirely made from these bars, and they were known as spring steel, but now they are either piled and welded for shear steel or cut up before hammering and melted in pots to form cast steel.

Shear Steel.—In manufacturing shear steel, plated bars are broken into suitable lengths, six piled together into what is known as a faggot, covered with fireclay and borax to prevent oxidation of the Carbon, heated in a hollow fire, and drawn out under the hammer to a bar. The bar is then known as single shear. In many cases the homogeneity of the steel is further increased by breaking the hammered bar through the centre, doubling it upon itself, re-heating, and re-hammering down to the required size; it is then known as double shear. Notwithstanding that the blooms during re-heating are protected by slag formed by the clay covering, the Carbon is always more or less oxidised, and the manufacturer is perfectly aware of this, and always selects a grade of bars of higher Carbon than he requires in his finished product, and he knows by experience exactly what allowance to make for this when he has trustworthy workmen. The single or double shear bar is afterwards, by forging and rolling, drawn into thin strips suitable for cutlery. Although no number of pilings and hammerings can ensure the same homogeneity that is obtainable with a metal that has been fused and cast, still for such purposes as the manufacture of high-class table cutlery, butchers' knives, and any class of knife which has an iron back with a cutting edge welded on, shear steel is superior to the finest cast steel, and has been able to hold its own against all comers. The word shear was originally applied from the fact that the blades of shears, formerly used for cropping woollen cloth, were always made as above described.

Case Hardening.—This process, which finds numerous applications in constructive engineering, is, like the surface carburising of armour plates, a special application of the cementation process. The object in the majority of cases is to obtain a hardened steel surface, while retaining a tough ductile

core of mild steel, but sometimes it is to improve the appearance of the article, for, with the increase of Carbon, tints and mottling may be obtained, which are impossible in lower Carbon steels. Various nostrums have been used for case hardening, and numerous attempts made to surround the process with mystery, by pretending that its success depends upon the use of a certain liquid for quenching, but the particular liquid used has no influence whatever, except in so far as all liquids have a greater or less hardening effect according to their conductivity and specific heats.

For case-hardening processes, various carburising materials are used, these include (1) solid materials, such as animal charcoal, bones, charred leather, compositions sold under various names and consisting of carbonaceous matter, and certain cyanides and nitrates, mixtures of barium carbonate and wood charcoal, &c.; (2) liquid materials, such as molten cyanide of potassium; (3) gaseous materials, such as illuminating gas, hydrocarbon vapours, &c. The only essential conditions for success are the use of a suitable form of Carbon, and care in heating to the required temperature, and for the length of time necessary to produce the depth of carburisation required for the particular class of work in hand. When solid carburising materials are used, these should be sifted free from dust, and the grains should be of uniform size. The addition of a small quantity of heavy hydrocarbon oil to the powder is an advantage, and prevents the absorption of moisture.

The hardening pots are made either of cast iron or wrought iron, the former are cheaper in first cost, but the latter last much longer. The pots should not be larger than necessary for the size of work in hand, and for small articles should be about $12 \times 10 \times 8$ inches. The pots must each have a close-fitting inside lid. There should be a layer of about $1\frac{1}{2}$ inches of the powder round each article to prevent it touching the others or the sides of the box, and the packing is finished with a layer of $1\frac{1}{2}$ inches on the top. The contents of each pot is made as compact as possible, the lid is put on, and the joint all round is well luted with clay. The charged boxes are now placed in a muffle furnace capable of being raised to about 1,000° C., and maintained at that temperature with great regularity. These muffles may be coal or gas-fired. The depth of case hardening, and also the amount of Carbon contained in the case, will vary with the temperature and length of time the operation lasts. For small work at a temperature of 1,000° for six hours a case about $\frac{1}{16}$ inch, containing about 0·8 per cent. of Carbon, will be obtained. After the desired time has been given for the absorption of the Carbon, the pots are withdrawn from the furnace, and allowed to become quite cold. The articles are then removed, and are brushed to remove all adhering matter. If the pots have been properly packed and luted up, the articles should be quite white, the more inclined to redness the articles are, the more imperfect has been the packing and sealing of the pots. The case-hardened articles are now placed in a muffle furnace and heated to about 800° C., and then quenched in cold or tepid water or oil, according to the purpose for which they are required. In some cases the whole contents of the box are directly emptied into water or oil, the separation of the articles from the powder being made by suspending a sieve a few inches below the surface. If the appearance of the articles is important, care must be taken that they are not exposed to the air in the fall from the box into the water, otherwise oxidation will result, and the skill of the workman is shown in avoiding this. On the other hand, many different tints can be given to the work by dropping it from a height, say, 3 to 6 feet, when oxidation neces-

sarily takes place, and a blue or streaked black coating will result. The colour can be varied by forcing air into the bath with the inlet water, so that the work meets with a further supply of Oxygen while chilling. The article is then taken out of the water and rolled in dry and warm sawdust, and then oiled. If the character of the steel to be case hardened is unknown, a test piece, in the form of a rod, may conveniently be used, this being stuck through a hole in the lid of the box, and withdrawn for testing as the operation proceeds.

The theoretical considerations of case-hardening processes have received considerable attention during the last few years, and many workers have recognised the important effect that nitrogen has on the penetration of the Carbon. In the case of non-nitrogenous material, such as sugar, charcoal, or anthracite, it is usually assumed that case hardening is effected indirectly by the air contained in the boxes forming Carbon Monoxide, which gas reacts with the iron, giving up some of its Carbon and forming Carbon Dioxide, this latter gas reacts with a further portion of Carbon, producing still more Carbon Monoxide, and so the process is continuous. Braune* and Petrén and Grabe† have shown that the Nitrogen content of steel is increased on cementing, and the last-named workers demonstrated that, in cementing, the Nitrogen content increases proportionately with increase in Carbon content in the steel, but only up to 1·0 per cent. Carbon.

G. Shaw Scott‡ carried out a series of experiments on case hardening under similar conditions, with non-nitrogenous materials, such as anthracite and hard coke, and with nitrogenous material, such as charred leather, with the result that the depth of case hardening was increased in the ratio of 10 to 1 when using the charred leather.

S. A. Grayson § has also investigated the action of different case-hardening materials, and has come to the conclusion that it is necessary to classify the different compositions both by the Carbon per cent. obtained in the case, and also by the graduation of the Carbon diffusion, this classification is necessary because the various compositions are each suitable for special classes of work. A high Carbon case would be very efficient for work where the pressure is fairly constant, but would be unsuitable for parts which had to resist repeated shocks, because of the strong tendency of the high Carbon case to chip or even peel off. The following are analyses given by this author for different case-hardening materials :—

	Bone.	Charred Leather.	Hardenite.
	Per cent.	Per cent.	Per cent.
Carbon,	8·0	69·0	44·0
Volatile matter and Hydrocarbons,	26·5	15·2	14·1
Nitrogen,	3·5	3·8	0·9
Ash,	60·0	3·5	37·5
Sulphur,	0·1	0·55	Trace
Moisture,	2·0	8·0	3·5

The "Hardenite" material consists of about 40 per cent. barium carbonate and 60 per cent. of charcoal. The chief action of the barium carbonate

* *Bihang till Jernkontorets Annaler*, 1907, p. 191.
† *Ibid.*, vol. lxi., p. 16.
‡ *Journ. Iron and Steel Inst.*, 1907, No. 3, p. 130.
§ *Ibid.*, 1910, No. 1.

seems to be due to the decomposition which takes place when this substance is heated in the presence of charcoal, barium monoxide, and carbon monoxide being formed, this carbon monoxide then takes an active part in the carburising.

Various methods have been adopted for the use of potassium cyanide as a case-hardening medium, the simplest method for special work and skin-hardening is to heat the article to almost a white heat, soak it into a cake of the cyanide, then reheat and plunge into water. A more satisfactory method of case hardening with potassium cyanide is to melt the cyanide—sometimes mixed with common salt to reduce the amount of poisonous vapours evolved—in a wrought-iron or cast-iron pot, and to soak the articles in the bath for a length of time determined by depth of case required, by this means it is possible to get quite deep case hardening. After soaking for the necessary time, the articles are removed, and either quenched in water or cooled, reheated, and quenched. Small iron parts are sometimes case hardened by soaking for 30 minutes in a fused bath consisting of 1 part of prussiate of potash and 10 parts of common salt, and then quenching in water.

Several processes and special furnaces have also been devised for case-hardening by means of gases; in these cases the work is brought to the correct temperature, and the Carbon-laden gases from the producers are introduced. J. C. Olsen and W. S. Weiffenback * investigated the case-hardening of steel by gases, and found the following to be the order of carburising ability—carbon monoxide, acetylene, methane. G. Charpy † has studied the action of carbon monoxide as a case-hardening medium, and found that cementation was possible at as low a temperature as 560°; he found, however, that between this temperature and 750° the cementation action was accompanied by a deposition of a layer of pulverulent Carbon on the specimen; above 750° there was no deposit of Carbon, but the rate of cementation increased up to a temperature of 900°, beyond which there was no apparent increase.

As an example of the utility of case hardening may be instanced the case of a crank spindle for a bicycle, where a combination of lightness, toughness, and wearing surfaces which will resist a file, are wanted. A mild steel may, therefore, be taken and machined to the shape required; it is then case hardened, and, on account of the distortion frequent in the latter process, is finally ground to finished size. The soft core of the metal, which is unaltered, will insure the toughness of the article.

* *Iron Age*, vol. lxxxiv., pp. 120-121.
† *Revue de Metallurgie, Memoires*, vol. vi., pp. 508-518.

CAST OR CRUCIBLE STEEL.

However carefully the steel converted bars may be selected, welded and re-welded, there is always a certain want of uniformity, and to obtain a thoroughly homogeneous material it is necessary to melt the materials in pots or crucibles.

Pot Melting.—The process of melting in pots was introduced into Sheffield about 1740 by Huntsman, and very little variation has taken place since in the method of carrying out the operation A sketch of a

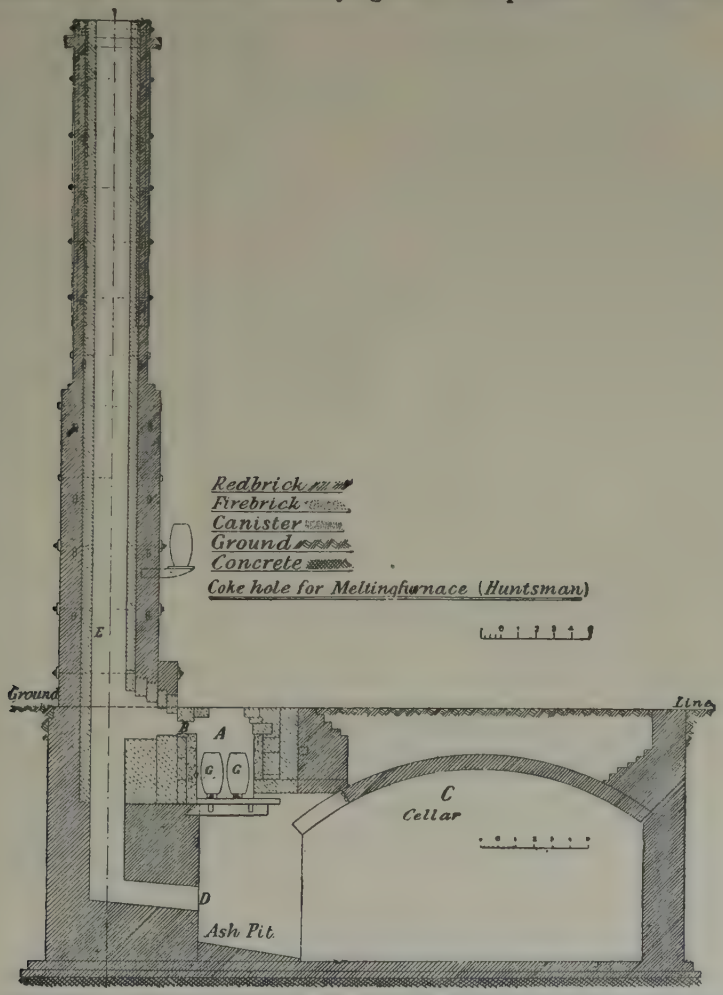


Fig. 185.—A, Melting hole or fire hole ; B, flue ; E, chimney ; D, opening communicating with chimney flue, which can be partially or entirely closed by a brick or sheet of paper to control the draught.

melting furnace is given in fig. 185, and it consists essentially of a "melting hole," which is a rectangular chamber, about 3 feet deep, and from $1\frac{1}{2}$ to 2 feet square, lined with fire-brick and rammed ganister. The top of

the furnace is at the level of the floor of the casting house, and is covered with a square of fire-brick, set in an iron frame with a projecting handle. The grate bars and ashpit are sunk below the floor, and an arched vaulted cellar below enables the workmen to gain access to these. Each melting hole is connected by a flue at the top with a stack which serves for five or six furnaces, usually arranged in a line on each side of the casting house, thus leaving the centre of the floor clear for casting operations.

The crucibles are made either of fireclay or of Graphite or Plumbago, and the greatest care is taken in the manufacture of these, as faulty pots mean very serious losses to the manufacturer. In this country clay crucibles are almost invariably used, and they are usually made in a shop adjoining the casting house. In Sheffield the pots are generally made from a mixture of Burton and Stannington clay, sometimes mixed with a certain proportion of Stourbridge clay, and a little China clay; a small quantity of ground coke and old pots is also generally added. The clays have to be very completely ground, and most thoroughly mixed together. This is usually done by treading in a trough, the pot-maker and his assistant kneading it with bare feet. Too much care cannot be exercised to insure the perfect working of the clay, as it is absolutely impossible to make good cast steel if the pots are defective, and in fact pot-making is an important branch of the manufacture of cast steel. The well-worked clay is cut into balls of sufficient size to make one pot, and moulded in an iron "flask," with well-fitting loose bottom, by pressing down a wooden or cast-iron plug. Both "flask" and "plug" must be well oiled, and the latter is centred by a pin at the bottom, which passes through the loose bottom of the flask. The plug is alternately raised and lowered until the clay is worked up to entirely fill the annular space between it and the flask, and then finally driven down with a mallet, after which it is withdrawn by turning it round. The edge of the crucible having been trimmed, it is placed upon a post, when the flask being released its weight causes it to drop, leaving the crucible standing upon the loose iron bottom of the flask, on the top of the post (fig. 186). The top of the crucible is now forced in by means of a conical mould to give it the barrel shape shown in the sketch (fig. 187). The crucibles are very carefully dried for two or three days on the shelf in the pot house, and then transferred to a shelf in the casting shop, near the flues, where they are dried for a period of at least ten or twelve days, and preferably for a month or six weeks. Each pot lasts a single day, can be used three times, and contains about 56 lbs. of metal for first heat, 44 lbs. for second, and 38 lbs. for the third. The object of reducing each successive charge is that the surface of the molten metal shall be at a different level in the pot, because the "flux" or scum, which floats on the surface, rapidly attacks the Silica of the pot, and cuts it away.

Clay pots are specially suitable for mild steel, as they do not carburise the metal, while it is almost impossible to get very mild crucible steel of uniform quality out of Plumbago pots. In Styria, on the Continent generally, and in America, Plumbago pots are commonly used; they consist of Graphite, with sufficient refractory argillaceous matter, to give the necessary cohesion during manufacture.

In this country Ceylon Graphite is preferred for the manufacture of Plumbago crucibles. It is carefully hand picked, then ground and sieved, mixed with fireclay in suitable proportions, and allowed to "mellow" before use. Selected Ceylon Graphite contains about 90 to 95 per cent. of Carbon, and as crucibles made from this material stand four or five charges, their longer life about balances the extra cost involved in their manufacture. But there is a disadvantage in using a pot a number of times, since the pots give up a greater proportion of Carbon to the first charge, and less with each

succeeding melting. Hence the product is apt to be irregular unless the

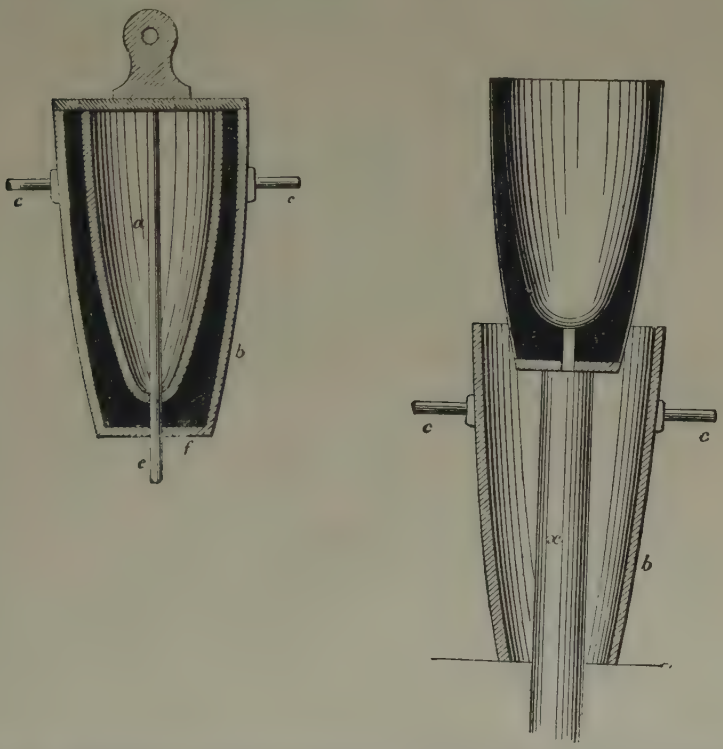
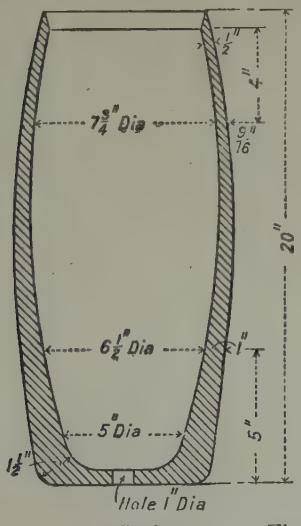
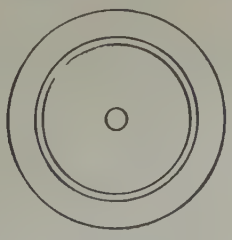


Fig. 186.—Manufacture of clay crucibles—*a*, Wooden plug; *b*, flask or mould; *c*, trunnion arms on flask; *e*, pin for centering plug, *a*; *x*, stripping post.



charges are arranged so as to meet the difficulty, which is practically almost impossible. As the crucibles are expensive, there is also the temptation to get the maximum number of charges from each pot, and thus with the last heat the walls sometimes become dangerously thin, and the charge has to be withdrawn before it is thoroughly "dead" melted.



Plan.

Fig. 187.—Crucible, as used in Sheffield.

Several moulding machines have been designed for crucible making, and are used in America, and in some large potteries in England, where crucibles are made a speciality, but as far as English practice goes, when the pots are made at the steel works, they are generally moulded by hand, although some steel makers have introduced moulding machines into their works.

Methods of Manufacture.—Cast steel is made of different "tempers," and may vary in percentage of Carbon from ·5 per cent.* to 2·0 per cent. or even more, according to the purpose for which it is required, and the percentage of Carbon may be arrived at in various ways.

For the great majority of purposes, when the highest class material is required, there can be little doubt that the best method is to use most carefully-selected blister steel—taking care to exclude all bars which are harder or softer than the temper required, and all "flushed" or aired bars—and to melt it in the crucible. Crucible steel made in this way will combine the greatest amount of hardness, with the maximum amount of elasticity when hardened; but there are two or three other ways by which very high class material may be made. Instead of blister steel best "cut bar iron," that is Swedish iron bars before converting, may be melted, and "fetched up" to the required "temper" by putting charcoal in the pot, or the purest varieties of broken pig-iron may be "let down" by melting it with cut bar iron. Another method which, for many purposes, is best of all, is to select blister steel of slightly harder "temper" than that required in the finished steel, and then to "let it down" to the exact "temper" by the addition of a small quantity of somewhat milder scrap.

When steel is made from unconverted bars they are cut up by shears into triangular pieces about 3″ × 3″ and charged into the pot with varying amounts of charcoal, from $\frac{1}{2}$ ounce to 8 ounces per charge, according to the temper required, and when the metal is completely melted a quantity of Spiegeleisen is added. In case of very mild temper steels sufficient carburisation is often affected by melting in Plumbago pots without any additions of Carbon, the Graphite of the pots with the Carbon of the Spiegel added producing the required "temper." The method of making cast steel by melting malleable scrap iron with charcoal and Oxide of Manganese was introduced into Sheffield by Mushet in 1801, and is still largely practised. Heath's process consisted in the addition to the charge of malleable scrap iron, of Manganese more or less reduced by Carbon at a very high temperature, or of a mixture of black Oxide of Manganese with carbonised pitch or resin.

In 1839 Mr. W. Vickers patented the use of a mixture consisting of 100 lbs. of wrought iron in the form of turnings or borings, 3 lbs. of black Oxide of Manganese, and 3 lbs. of the best ground charcoal. In recent years there is no doubt that considerable quantities of crucible cast steel have been made from mild Bessemer or Siemens scrap instead of best Swedish "cut bar iron," but the quality is always inferior, and cannot compare with the best steel made from selected cement bars, or with Styrian open hearth bars.

Whatever variation there may be in details as to the mixture, the process is carried out as follows:—The pots, previously well dried and annealed by heating to redness in an annealing grate, are placed in the furnace upon a circular disc of fireclay or a fire-brick resting on the fire-bars. The fire is then made up level with the top of the pot and the heat gradually raised for about half an hour, after which a little sand is thrown into the pot to fill the hole made by the central pin in moulding, and this also frits the pot to the

* Crucible steel is made with a much lower percentage of Carbon than ·5 per cent., for some special purposes as low as ·10, but ·5 per cent. is about the limit for "cast steel" as used for tools.

fireclay disc. The broken blister bars or scrap, charcoal, &c., as the case may be are then put into the pot through an iron funnel called a "charger," the lid placed on the pot, the furnace filled with coke and the fire urged. In about fifty minutes the fire is poked down and made up again with more coke, and when this is burnt off the lid is removed and the pot searched with an iron rod to see whether the charge is completely melted, and if not the fire is poked down and the furnace again filled up with coke. The temperature of the furnace is regulated by the "puller out" by inserting bricks in the melting or cellar hole flue (D, fig. 185). The cellar hole flue is also often controlled by the somewhat crude but effective method of closing the hole by means of a sheet of paper which is placed over the hole, and when it is expedient to admit more air a hole is made in this with an iron bar, and it is curious to note the ease with which a skilful man will regulate the heat by this means. After the second or third fire has burned down, the head melter carefully inspects the pots and gives final instructions to the "puller out" as to when the metal is ready for "teeming." At the word from the melter the pot is removed by means of tongs from the furnace to the furnace floor, cleaned from coke and slag on the outside, the lid taken off, and the scum or slag skimmed off the surface of the molten steel. This is then poured into a cast-iron mould made in two halves, clamped together with rings and wedges, to facilitate the withdrawal of the ingots afterwards. To prevent the ingots adhering to the mould, the interior of the latter is reeked or covered with a wash of coal-tar soot before using. Immediately after teeming the pots are taken back to the melting hole, cleared from the adhering clinker on their sides and bottoms, and replaced in the fires when they are ready for another charge. The first heat usually takes about $4\frac{1}{2}$ to 6 hours, but the second and third will not, as a rule, take more than $2\frac{1}{2}$ to 3 hours.

Melting the Steel.—The melting of the higher qualities of steel is a process which requires the greatest judgment and skill, and the quality of the final product will to a very great extent depend upon the technical skill and sound judgment of the head melter. If the steel is not kept sufficiently long in the furnace—that is to say, if it is not properly "killed"—it will teem fiery and produce a honeycombed ingot, and if it is poured at too high a temperature the same result will follow. If kept too long in the furnace the steel will teem dead, and will be brittle if hard steel, and deficient in tensile strength if a low Carbon steel, and the fracture of the ingot will have what is known as a "scorched look." If, again, the molten steel be chilled too much before it is cast, detected by the stream skimming over as it is teemed, the ingot will be honeycombed, and the fracture will be dull in colour. Should a piece of coke by any chance find its way into the pot during the melting, the ingot will have a bright sparkling fracture ; in technical phraseology, it will be said to "stare," and will work "hot short" under the hammer.

There is always a tendency for mild steel to rise in the ingot moulds, and the mouth of the ingot mould is closed with a plug of cast or wrought iron or with sand to prevent, as far as possible, the top of the ingot from becoming spongy. In ingots with 1 per cent. or more of Carbon, if properly melted, the steel in the centre of the ingot will settle down as it cools, leaving a hollow space in the middle of the top of the ingot known as a "pipe." This should be not less than 3 to 5 inches deep.

Treatment of Ingots.—The waste in crucible steel manufacture during melting varies somewhat, but is generally at least 10 per cent. of the charge. The ordinary sizes of ingots are $2\frac{1}{2}$ and 3 inches square and about 30 inches long, and other sizes are made up to 12-inch ingots, but these are only cast when specially required, as these larger sizes have to be cogged, and involve

extra expense in the subsequent treatment. When large and heavy ingots are required several pots are employed. In special cases the contents of a large number of crucibles are poured into a ladle from which the ingot mould is filled, care being taken to have a constant stream of fluid steel from the beginning to the end of the cast. In this way castings weighing as much as 70 tons have been made. When the ingots are cold they are topped—that is to say, the hollow part or pipe is broken off until the ingot shows a sound fracture. The ingots which have been improperly melted are rejected, and the others are graded according to Carbon contents. Between the range of 1 to 1·5 per cent. of Carbon an experienced man will readily be able to detect by fracture a difference of ·1 per cent. of Carbon.

The next operation is to reduce the ingot to the form or section required by the consumer, and for this purpose it must be re-heated and forged or rolled. As the value of the steel for the particular purpose for which it was manufactured depends almost entirely upon its Carbon content, it will be obvious that the greatest care must be taken not to oxidise the Carbon to any appreciable extent during reheating, and all overheating must be most carefully avoided. With this object in view the steel must be sprinkled with ground fireclay or sand and borax before being placed in the furnace, and continually turned round in the fire to ensure equable heating quite through the bar, or until it is thoroughly "soaked." On the other hand, it is very important not to subject the ingot to too long a soaking, as this rapidly deteriorates the quality of the material. Whether the ingots are rolled or hammered depends on the shape and size of the finished bar. Almost all the manufacturers, even the smaller ones, have facilities for forging at their works, but it is only in a few of the larger works that the cogged billets can be rolled. There are a large number of small manufacturers, and as tool steel is a relatively costly material, with a limited demand, it has been found desirable to provide public mills and forges where the ingots can be rolled or forged at a trade list price, and even the largest firms send their ingots to these when making unusual sizes. The use to which a bar is to be put and the section and size usually determine whether it is to be rolled or hammered. Thus steel to be used for taps is forged so as to give greater density, while that for punches is rolled to ensure greater uniformity. Best squares, from sizes of half-an-inch and upwards, are always forged; octagons are also forged from a square bar or rolled into square bars and planished afterwards under the hammer. Small rounds are best rolled, while triangular sections are always rolled, as it is so much easier to produce the required sizes in this way. Small flats are always rolled; large flats are also often rolled, though sometimes they are forged, as this gives sharper and better defined edges. In forging a steel bar one-half of the ingot is heated and forged, while the other end is held in a pair of tongs. With a little experience it is easy to distinguish a forged from a rolled bar; the rolled bar is smooth and uniform throughout its length, showing faint longitudinal lines due to the rolls, while a forged bar shows the marks of the forging. Usually also there is a difference towards the centre, owing to the centre of the bar having been heated a second time after it has been finished to size. Formerly the old tilt hammer was used for forging, but this has now been almost entirely superseded by small steam hammers.

Temper of Cast Steel.—It has already been pointed out that the "temper" of steel depends, assuming it to have been made from high class material and with proper care, upon its content of Carbon. The particular percentage for any special purpose can only be determined by large experience, and as pointed out by Henry Seebohm,* in his paper before the

* *Iron and Steel Inst. Journ.*, 1884, vol. ii.

Iron and Steel Institute on crucible steel, in all cases, where this high-class steel is required, it is greatly to the interest of the user to explain fully his requirements to the manufacturer when ordering, instead of ordering a steel with a certain percentage of Carbon. For the more common purposes for which crucible steel is used, Seebohm recommends steels of the following composition, and his remarks on special properties of different Carbon steels are so to the point that it will be better to quote his exact words :—

"*Razor Temper* (1½ per cent. Carbon).—This steel is so easily burnt by being over-heated that it can only be placed in the hands of very skilful workmen. When properly heated, it will do twice the work of ordinary tool steel for turning chilled rolls, &c.

"*Saw-file Temper* (1⅜ per cent. Carbon).—This steel requires careful treatment ; and although it will stand more fire than razor steel, should not be heated above a cherry-red.

"*Tool Temper* (1¼ per cent. Carbon).—The most useful temper for turning tools, drills, and planing-machine tools in the hands of ordinary workmen. It is possible to weld cast steel of this temper, but only with the greatest care and skill.

"*Spindle Temper* (1⅛ per cent. Carbon).—A very useful temper for circular cutters, very large turning tools, taps, screwing dies, &c. This temper requires considerable care in welding.

"*Chisel Temper* (1 per cent. Carbon).—An extremely useful temper, combining as it does great toughness in the unhardened state, with the capacity of hardening at a low heat. It is consequently well adapted for tools when the unhardened part is required to stand the blow of a hammer without snipping, where a hard cutting edge is required, such as cold chisels, hot setts, &c.

"*Sett Temper* (⅞ per cent. Carbon).—This temper is adapted for tools where the chief punishment is on the unhardened part, such as cold setts, which have to stand the blows of a very heavy hammer.

"*Die Temper* (¾ per cent. Carbon).—The most suitable temper for tools where the surface only is required to be hard, and where the capacity to withstand great pressure is of importance, such as stamping or pressing dies, boiler cups, &c. Both the last two tempers may be easily welded by a mechanic accustomed to weld cast steel."

Chemistry of the Process.—The chemical reactions which take place during the melting of crucible steel will vary from oxidising to reducing, according to the mixture of materials charged and the crucibles used. In cases where rusty scrap iron and Oxide of Manganese are used in clay crucibles, at first a more or less oxidising slag will be formed, but as the steel gets completely melted the Oxide in the slag will be gradually more and more reduced by the Carbon present, and its oxidising action therefore becomes less and less energetic, and finally, during the "killing" of the steel, the reducing conditions so predominate, that not only iron, but even Silica, is reduced from the slag and crucible walls, and passes into the metal. This, in all probability, is the explanation of "killing," as we know in the case of mild steel that the addition of small quantities of Silicon has a very marked effect in producing soundness. In 1861, Sir Henry Bessemer showed that very small additions of Silicon had a remarkable effect in producing solid ingots, and, according to the experiments of Turner,* the addition of 0·02 per cent. of Silicon was sufficient to make "lively" Bessemer basic metal quiet in the moulds, and give solid ingots. When Plumbago crucibles are used the reduction of Silicon from the crucible is much more marked, and Howe† gives analyses showing that as much as 0·6 per cent. of Silicon, in

* *J. Chem. Soc.*, vol. li., p. 136.
† Howe, *Metallurgy of Steel*, p. 313.

some cases, is reduced, and passes into the metal during melting, and the addition of carbonaceous material to the charge tends to produce the same result, although to a less extent. Under ordinary conditions of work with clay crucibles, it is only with the greatest difficulty that steel, containing less than 0·1 per cent. of Silicon, can be obtained, even when the purest material is used. The addition of Ferro-Manganese, probably partly by increasing Carbon content, tends to increase the amount of Silicon reduced, whilst Oxide of Manganese, or any other oxidising agent, has the reverse effect. High temperature and length of "killing" also favour the reduction of Silicon, other things being the same. There is no elimination of Phosphorus, but, in fact, a slight relative increase, and Sulphur also slightly increases, probably being taken up, to a very small extent, from the furnace gases, but this is generally very slight.

Very low Silicon steel can be made by the addition of small quantities of Aluminium shortly before teeming, as this seems to have the same effect in quieting the steel as Silicon, and enables "killing" to be dispensed with, so that practically very little Silicon is reduced, and passes into the steel. Great care must be taken not to add too much Aluminium, ·02 to ·03 per cent. being all that is required. The use of Aluminium is now becoming very general in crucible steel manufacture as a substitute for killing.

Gas-fired Crucible Furnaces.—Numerous attempts have been made from time to time to introduce gas regenerative furnaces for crucible steel making, but notwithstanding that great economy of fuel is effected they have not been generally adopted. Various reasons have been given for this, but the principal objection appears to be that it is difficult to heat the entire crucible to the same temperature, the bottoms being always somewhat cold, and consequently that equable casting temperature so essential to the production of the highest class of crucible steel is not regularly obtained. A furnace designed by Messrs. Dawson, Robinson & Pope especially to meet this difficulty is shown in fig. 188, and is giving excellent results at the works of Messrs. Jessop & Sons, Sheffield. The gas and air ports in this furnace are lower than the bottom of the crucible, and it is especially designed so that all the separate holes containing the pots or crucibles may be kept at an even temperature. The saving in fuel is said to be at least £2 10s. on every ton of steel made, only $1\frac{3}{4}$ tons of slack being used as against 3 tons of high-class coke in ordinary "coke-hole" practice.

The pot holes are arranged to hold six crucibles, and three such holes are connected with one set of regenerators—*i.e.*, two gas and two air regenerators, as shown in the sketch. The pot holes are sunk below the floor level in the usual way, and each has four ports connected with the regenerators —two with the air and two with the gas—so that gas and air enter through two and meet at the entrance to the pot hole at the bottom, where combustion takes place. The flame travels in a horse-shoe direction round the crucible, and the products of combustion pass down the other ports, heating up the other pair of regenerators. In the sketch (fig. 188) air and gas respectively are shown to be entering by the six ports, *a*, *a*, *a*, and *b*, *b*, *b*, from regenerators A and B, and the products of combustion to be passing down ports *c*, *c*, *c*, and *d*, *d*, *d*, to heat up regenerators C and D. The three pot holes form one furnace, and one gas and one air valve reverse the direction of the flame in all three holes. The position of the chimney is arranged to suit local circumstances, and any form of reversing valve similar to those used in ordinary Siemens furnaces may be employed.

Another gas-fired crucible furnace is the "New Form Siemens," which,

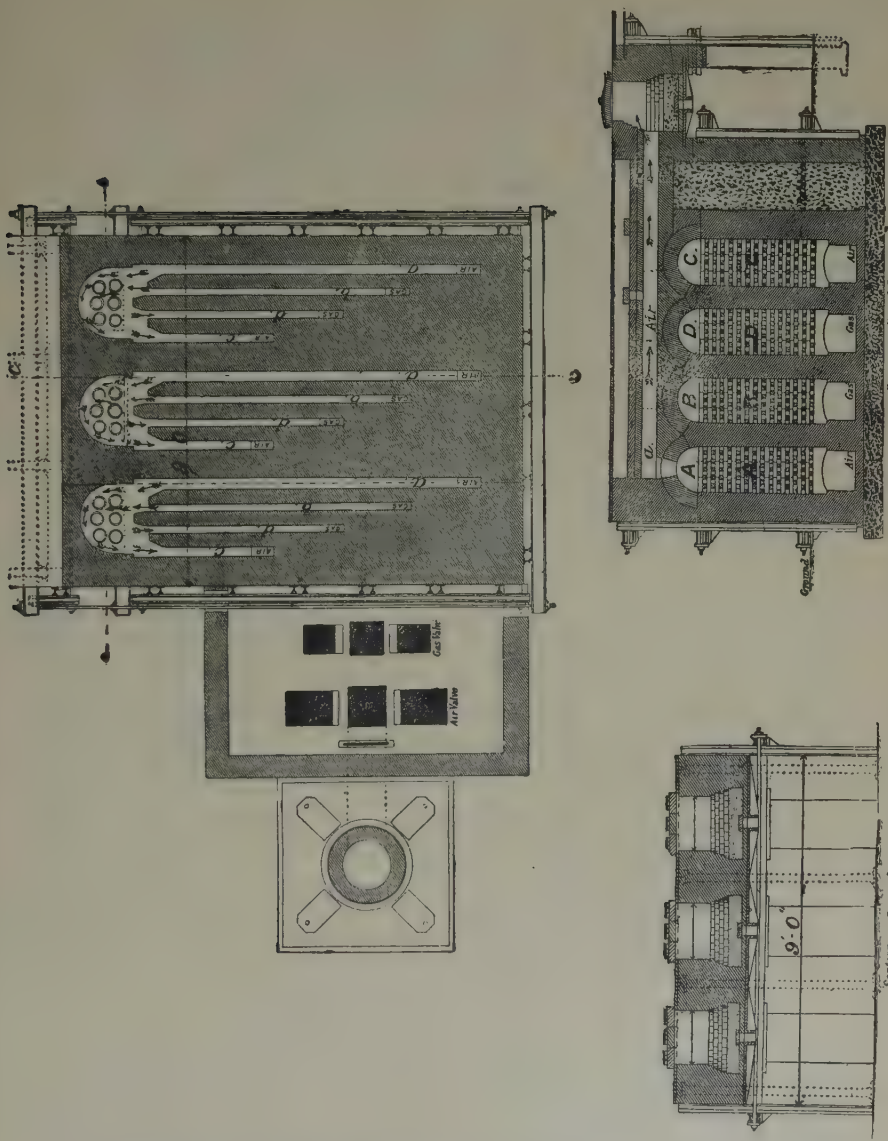


Fig. 183.—The Dawson, Robinson & Pope Gas Crucible Steel Furnace.

The air and gas respectively are entering by the six ports, *a*, *a*, *a*, and *b*, *b*, *b*, from the air regenerator, A, and gas regenerator, B, and products of combustion are passing down ports *c*, *c*, *c*, and *d*, *d*, *d*, heating up regenerators C and D.

as applied to open hearth work, is described in Volume II. The crucible furnace differs, of course, from the open hearth "New Form" in constructional details, but it embodies the same general principles, and thus realises similar advantages.

This furnace (figs. 189, 190, and 191) has given excellent results at Sheffield and elsewhere. A six-pot furnace has been erected at Sheffield University, and I am informed that it is in every way satisfactory, and that there is not the least trouble with cold bottoms to the crucibles. Furnaces of his newest design with twelve pots are stated by Mr. Frederick Siemens to be giving equally good results at steel works both in this and other respects.

The fuel consumption is said to vary from 19 to 25 cwts. of slack or nut coal, according to the quality of the coal used and the class of steel required, and this is equivalent to a saving of from £2 10s. to £3 per ton, taking English prices for coal and coke. The pots also last a greater number of heats, and at one Sheffield works are said to be used four and sometimes five times, against three times in the ordinary coke-hole, and the furnace itself is stated to have worked for 18 months without stopping for repairs. Mr. Frederick Siemens informs me that at one works in Germany the total saving in pots and fuel amounted to £4 12s. 3d. per ton of steel produced. This saving will vary with the relative prices of coke and coal and refractory materials in different districts, but must in any case be considerable.

The economy in fuel, ease with which gas can be regulated, freedom from clinker on pots—which should lead to considerable economy in this direction—offer so many advantages over the coke hole that, notwithstanding past failures of gas furnaces, there seems every prospect of gas-fired furnaces being very largely adopted in crucible steel melting. In the States gas furnaces are used almost exclusively. Mr. R. A. Hadfield, writing in the *Iron and Coal Trades Review*, 1895, stated that in Pittsburg they were melting by natural gas with one-fourth to one-fifth the amount of fuel used in "pot" furnaces in England.

Taking the weekly production of crucible steel in Sheffield at 1,000 tons, each ton requires about 3 tons of coke, equal to 150,000 tons of coke per annum, costing £112,000 to £180,000, at 15s. to 25s. per ton. Furnaces run in America by producer gas do not use more than 15 to 20 cwts. of "slack" per ton of crucible steel melted, costing 6s. to 8s. per ton, which, if the same were done at Sheffield, would mean a saving of from £100,000 to £120,000 per annum.

Howe* gives the cost of fuel for producer gas melting crucible steel as about 90 cents per ton, as against 50s. to 60s. at Sheffield, but this is taking slack at about 85 cents per ton of 2,000 lbs., which is a much lower price than that at which good slack can be obtained in England.

Where crucible steel is used for large castings the ordinary Siemens furnaces with a flat hearth seem to give excellent results, and at the Krupp Works are almost, if not entirely, used for crucible steel melting; but the conditions are somewhat different to those when the steel has to be teemed into small cast-iron moulds, and any slight variation in temperature between the top and bottom of the crucible is undoubtedly of more importance in the latter case.

* Howe, *Metallurgy of Steel*, p. 310.

PLATE XV*a*.—"New Form Siemens" Steel Furnace.

[*To face page 260.*

The gas made in the gas producers, *a*, *a*, passes into the main gas flue, *c*, in which are the gas valves, *d*. According to the position of these valves the gas passes along one or other of the gas flues, *g*, to the port, *i*. The air enters the air valve, *e*, passes along one or other of the flues, *h*, through one of the regenerators, *f*, *f'*, and thence to the port, *i*. The products of combustion pass in the reverse direction to the air, and so reach the chimney flue, *m*. A is a damper by means of which any gas producer may be shut off for repairs or when less gas is required. L is a hole communicating between the air flue and the gas port, so that a small flame of air burns in the gas and further heats it before it reaches the furnace and is completely burnt in its passage along the bed, *b*.

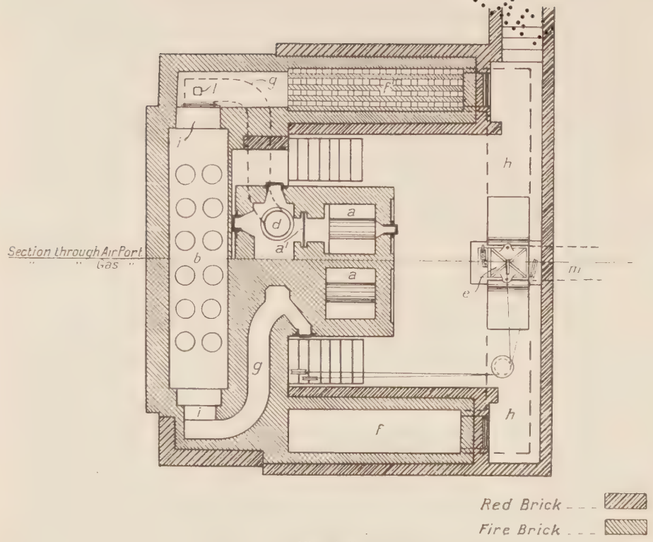
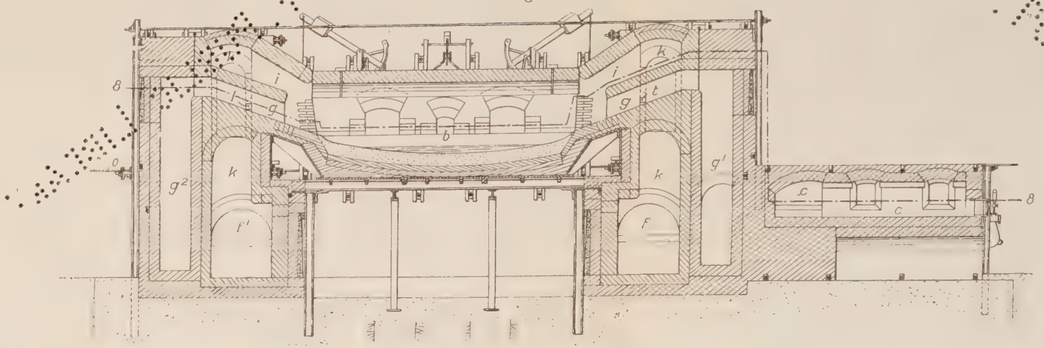


Fig. 189.

Fig. 190.



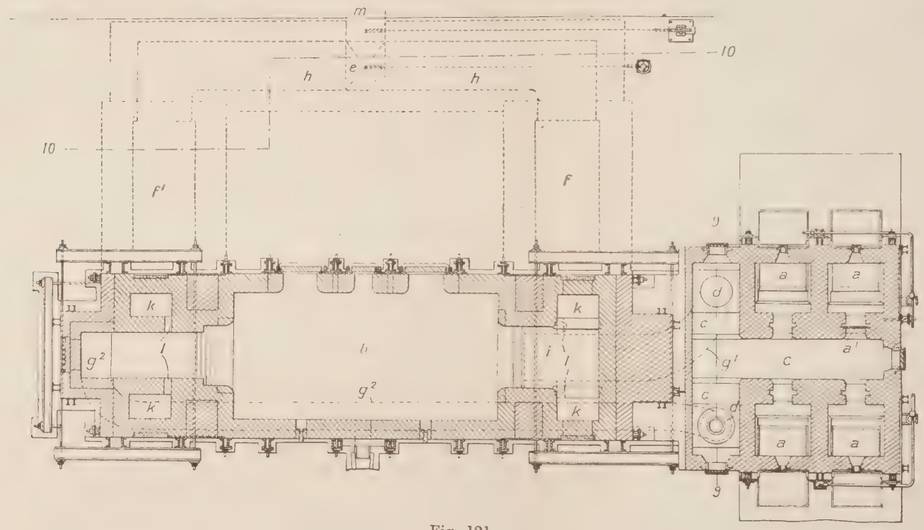


Fig. 191.

CHAPTER XI.

ELECTRIC SMELTING OF STEEL.

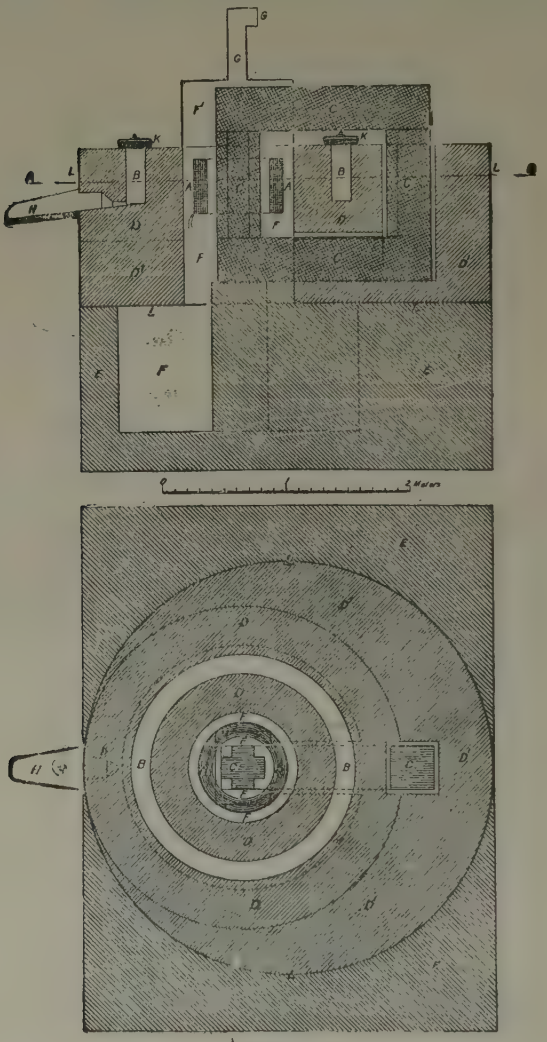
THERE are three distinct types of electric furnaces which are claiming the serious attention of metallurgists, and all three are now being employed to manufacture steel on what may be considered a commercial scale, although at present they are confined to the production of high-class Carbon and Special Steels from cold scrap, or to the refining of molten open hearth or Bessemer steel to produce steel of better quality. The three types of furnaces are (1) The Induction, (2) The Arc Resistance and Resistance, and (3) The Arc.

THE INDUCTION FURNACE.

This type of furnace is a large crucible in which the steel is melted by an induced current out of contact with any electrodes, completely protected from the action of any furnace gases, and practically protected from oxidation. It gives, from a metallurgical point of view, by far the nearest approach to the conditions of the crucible process, and provided the same care is taken in the selection of the raw materials a finished product, equal in all respects to crucible steel, is obtained. The best known furnace of this type is the Kjellin furnace, which has been in operation at Gysinge, Sweden, since 1900. Figs. 192 and 193, taken from the Canadian Commission Report, are a plan and sectional elevation of this furnace. This furnace is in effect a step-down transformer, in which the contents in the hearth or crucible form the secondary circuit of the transformer. The furnace is of 225 H.P. capacity, and to the primary A A, Fig. 192, is delivered an alternating current of 90 amperes and 3,000 volts, which induces a current in the secondary B B of 3,000 amperes and 7 volts. The primary A A consists of an insulated copper wire wound round one leg of the laminated core C C C C, which forms the magnetic circuit. Where an alternating current is passed through the coil it excites a magnetic flux in the core, and the intensity of the current induced in the steel is then almost the same as the primary current multiplied by the turns of the wire in the primary coil. The tension of the current is naturally reduced in almost the same ratio as the intensity is increased. In this way it is possible to use an alternating-current generator of high tension, and to obtain a current of low voltage and great intensity in the furnace.

The furnace is basic lined, and steel of any required grade can be made exactly in the same way as in the ordinary crucible process (1) by melting blister bars of slightly higher "temper" than the steel required; (2) by melting selected blister bars of distinctly higher "temper," and "letting down" with the required percentage of low Carbon steel scrap; and (3) by melting best Swedish pig-iron with sufficient Walloon iron to give steel of the required "temper." Commercially, however, the method employed in Sweden is to use pig-iron and best Walloon scrap, and by this means any grade of steel from 0·1 to 1·5 per cent., or even higher Carbon, can be obtained.

In making dead soft steel it is necessary to melt Walloon iron practically alone, and for this purpose it is essential to have ample electrical power available to melt the charge rapidly, as otherwise the oxidising slag which



Section A B

Figs. 192 and 193.—Kjellin Furnace. Vertical Section through the Tap Hole and Sectional Plan on A B.—A A, Primary coil of insulated copper wire wound round laminated core, C, and to which is delivered alternating current of 90 amperes at 3,000 volts; B B, annular crucible or hearth, in which charge is melted and forms the secondary; C C, laminated core; D′ D′, firebrick; D D, Silica or Magnesite brick; E E, ordinary brick foundation; F F, air space for cooling primary; F′ and G, iron cylinder with pipe attached to maintain a current of air flowing round primary; H, spout from taphole; K K, covers for annular crucible; L L, cylindrical iron casing of furnace. The covers of the crucible are on a level with the working floor, and the furnace is charged by removing these and throwing the scrap and iron into the crucible B.

is liable to be formed, when present even in small quantities, will tend to produce wild metal.

In starting the furnace, a little molten pig-iron is poured into the circular trough B to form the secondary circuit, and at the finish of each heat, sufficient molten steel is left in the furnace to maintain this circuit. After tapping, cold pig and scrap are charged, and, as they gradually melt, fresh additions of scrap and pig-iron are made from time to time. The charging is done by removing the covers from the top of the annular hearth, and any accumulation of slag formed by oxide on the scrap is raked off the top of the molten metal and removed with iron bars in a pasty condition. The time taken to convert each charge varies from six to eight hours, according to the grade of steel required, the longest time being required for dead soft steel, as it takes longer to melt, and needs more time to get a sufficiently good tapping heat on the metal; consequently the consumption of energy will be greater in the case of low Carbon than high Carbon steel. Slight oxidation takes place during the operation, as materials which have an average composition of 1·4 per cent. of Carbon yield a steel with about 1·1 per cent., showing that about ·3 per cent. is oxidised during the working of the charge. This is probably due almost entirely to the rust on the scrap used, and not to atmospheric oxidation; and it is so slight as not to affect appreciably the oxidation of the impurities present, although Silicon may be to some extent removed.

The following may be taken as the average composition of the materials used and the steel produced :—

Materials Used.			Steel Produced.	
	Best Swedish Pig Iron (White).	Walloon Bar Iron.		Average Composition.
Carbon, . . .	4·400	0·200	Carbon, . . .	1·3 to ·50
Silicon, . . .	0·080	0·030	Silicon, . . .	0·200
Sulphur, . .	0·015	0·003	Sulphur, . . .	0·010
Phosphorus, . .	0·018	0·009	Phosphorus, . .	0·010
Manganese, . .	1·000	0·120	Manganese, . .	0·200
Arsenic, . . .	0·015	0·008	Arsenic, . . .	0·020
Copper, . . .	0·035	0·035	Copper, . . .	0·032
			Aluminium, . .	Nil.

The Carbon and Silicon in the finished steel are varied by regulating the charge, and by the addition of Silicon pig-iron; and by suitable additions, special steels or steel alloys of any composition can be made. Dead soft steel can also be made, and when the author was at Gysinge such a charge was made in his presence, the only difficulty being the removal of the slag, as there was no means of withdrawing it from time to time. In making the high Carbon steel, so little slag is formed that it can be readily removed from the top of the bath, and consequently no slag hole for withdrawing it had been provided, but with slight structural alterations to the furnace mild steel could be easily made.

Various modifications of the Kjellin induction furnace have been introduced during the last few years, amongst others the Frick and the Hiorth furnaces, but there is no new principle involved in either of these, and they vary only in detail from the original furnace at Gysinge, although both

inventors claim considerable practical advantages for their furnaces. A 10-ton Frick furnace is working successfully at the Krupp Works at Essen.

One great disadvantage of the Kjellin type of furnace from a practical point of view is the narrow ring channel forming the hearth of the furnace, and this is especially so for furnaces of comparatively large capacity. This form of furnace offers difficulties in charging, repairing, &c., and if refining has to be done by very basic infusible slags, it is difficult, if not impossible, to maintain these slags sufficiently hot, and consequently fluid, to do the necessary work, as the induced currents prefer the path of least resistance—namely, that of the metallic base. Further, the power factor of these furnaces is always low, and although this may be improved by reducing the frequency of the alternating current, it has been found that such an unusually low frequency is required for large furnaces that very expensive generators are necessary. However, furnaces up to 10 tons capacity are in successful operation. These various disadvantages, both metallurgical and electrical, have been largely overcome by the designers of the Röchling-Rodenhauser furnace, which may be regarded as a combination of an induction and resistance furnace.

Like the Kjellin induction, the Röchling-Rodenhauser furnace, Figs. 194 and 195, is essentially a transformer with a single primary winding A round both iron cores H of the transformer. The secondaries are two in number, one is the molten bath in form of an 8, the channel D between the two cores being very broad. The other secondary is the copper winding B, which is connected with the metal plates E. These metal plates are inserted into the furnace walls F in such a way that the currents pass from the winding B through the plates E, and through the mass G of highly refractory electrolytic conductors (of the same nature as those used as filaments in the Nernst lamp) to the molten mass D. In this way the molten mass D is subjected to a double heating effect, one direct by induction and the other from the currents passing between the opposite sets of electrodes E. The direction of the currents in the bath at a certain moment is indicated by arrows in the illustration.

In order to protect the windings against the effect of high temperatures, thin-walled copper cylinders are provided, through which is conducted an air blast passing out of the tubes N_1N_2. The transformer iron contains ventilation slits H. These methods of cooling have been found to be perfectly sufficient during several months' operation.

The charging door is at one end of the furnace, the tapping door at the other end. On account of the method of operation of the furnace the molten charge is kept in sufficient circulation so that all manual operations are restricted to taking care of the right formation of slag and to the tapping of the metal. As shown in Fig. 196, the whole furnace is built as a tilting furnace.

The latest development in connection with this furnace is its operation by a three-phase instead of a single-phase current, which enables a 15-ton furnace to be operated with a frequency of 50 periods instead of 25, and standard three-phase generators to be used instead of specially constructed expensive generators. Figs. 194, 195, and 196 show this furnace in sectional elevation and plan. It is claimed that a special feature of this furnace is the rotation of the charge due to the presence of a rotatory field, as in an induction motor, which insures an automatic circulation in the bath. The furnace is, like the Kjellin furnace, basic lined, and is being used almost exclusively for refining molten steel made in Bessemer or open-hearth process, although, provided it is started with a small quantity of molten metal, there is no reason why cold scrap and pig should not be charged.

When starting with cold scrap rings of metal embedded in scrap turnings, &c., are placed in the furnace, and the current switched on; the rings soon become heated, and heat the surrounding material, so that the entire charge melts rapidly.

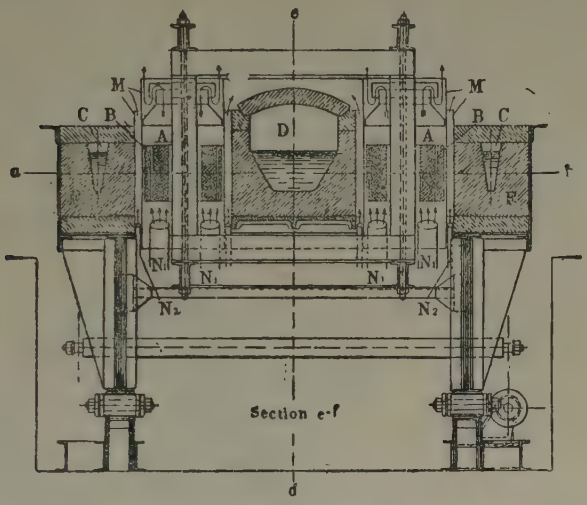


Fig. 194.—Sectional Elevation of Röchling-Rodenhauser Furnace.

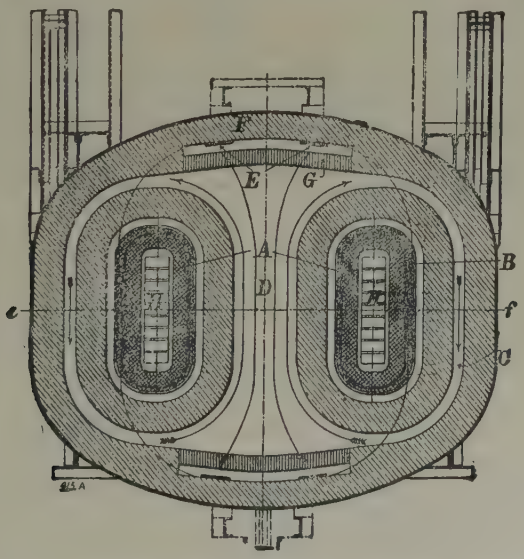


Fig. 195.—Sectional Plan of Röchling-Rodenhauser Furnace.

From the practical metallurgical standpoint, this furnace has many advantages over the Kjellin furnace, as materials can be readily charged into the wide portion of the hearth. Sufficient heat can be obtained to maintain a fluid slag for refining which can be readily poured or raked off the

surface of the metal, and the metal itself when the charge is finished can be poured into a ladle. The central chamber or main hearth is also readily accessible for repairs, as these can be effected from either end through the doors provided. In working a heat either cold scrap or molten steel is charged into the furnace with suitable additions of lime and oxide, and when these are completely melted the slag is poured off, and further additions of lime and oxides added to form a new slag and complete the refining; if necessary this operation can be repeated until metal of the required degree of purity is obtained.

Although cold scrap can be used, the furnace is far better adapted for refining molten metal, and it is in this direction that it may be expected to do the best work. When refining molten metal the amount of energy consumed will vary from 120 to 300 kilo-watt hours, according to the degree of purification required.

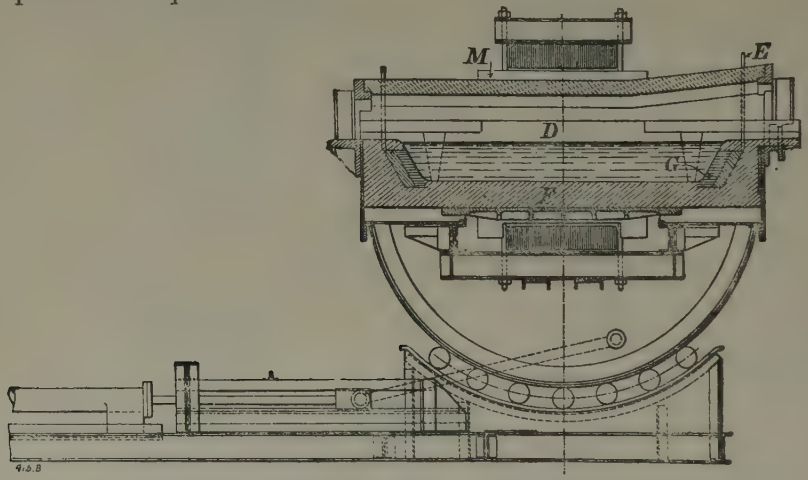


Fig. 196.—Röchling-Rodenhauser Furnace. Section through centre of bath.

A furnace at Völklingen has been in operation for some time refining molten metal from a basic Bessemer converter, and others have been erected in different parts of the Continent.

A very similar furnace somewhat modified in respect to electrical details has been designed by Hiorth, but the difference from the metallurgical standpoint is so slight that no detailed description is necessary.

THE ARC RESISTANCE FURNACE.

In this type of furnace the heat is generated largely by the arc, and, to a smaller extent, by the resistance offered by the whole or a portion of the furnace charge to a very powerful electric current. It is represented by the Héroult, Keller, Girod, and Grönwal furnaces, all of which are in commercial operation,

THE HÉROULT PROCESS.

The Héroult furnace is a tilting furnace similar, as regards the tilting section, to the Wellman or Campbell furnace, and lined with basic material. Two electrodes pass through the roof, and a water-jacket

surrounds them supported upon the roof. An alternating current of about 4,000 amperes at 110 volts is used for a 3-ton furnace, and the intensity of the current passing through the bath of steel is regulated by raising or lowering the electrodes. This may be done by hand, or by a specially designed automatic regulator, which controls separately the position of each electrode by means of a small motor placed at the back of the furnace, and geared to the mechanism supporting the electrodes. The motor is controlled by electric mechanism actuated by variations of the voltage or current below or above certain defined limits. At the ends of the furnace, where the gas ports are in the ordinary Wellman furnace, are charging doors, and in front is a movable door over the pouring spout. In starting the furnace

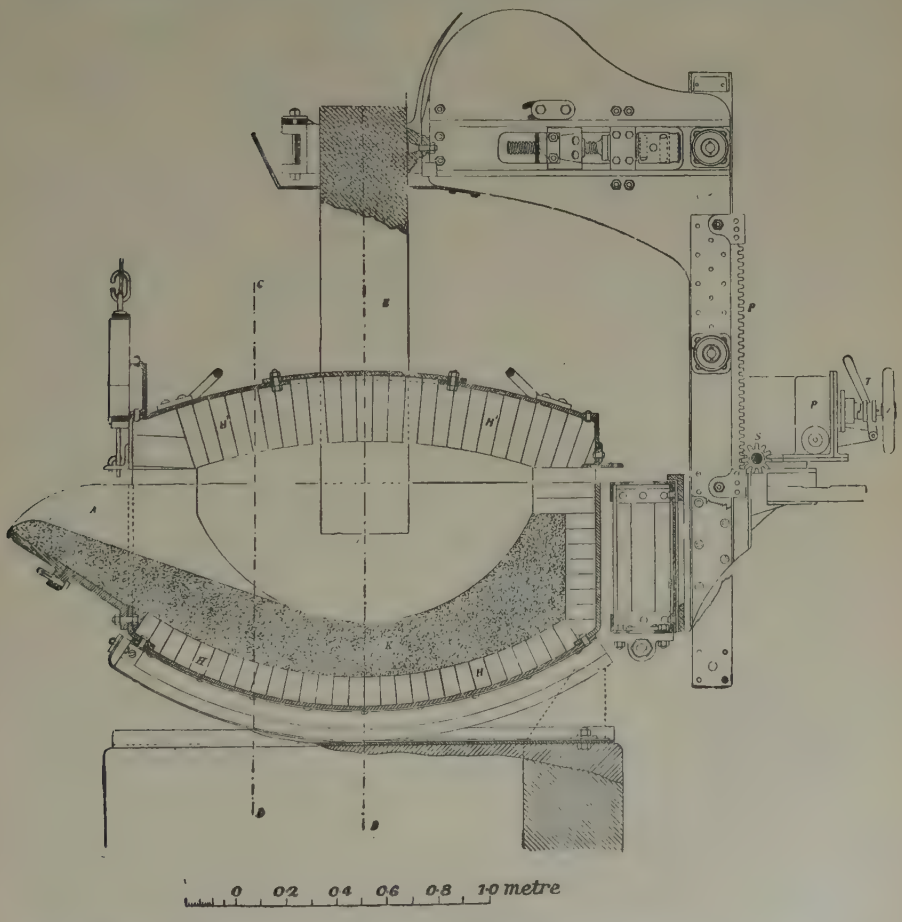


Fig. 197.—Vertical Section through the Pouring Spout of the Héroult Furnace at La Praz.—A, Pouring spout; E, suspended electrode, of which there are two passing through roof; H, basic or burnt Dolomite bricks; H′, Silica bricks of roof; K, rammed basic material; P, motor for driving automatic regulator; T, lever for throwing motor, P, out of action; Z, hand-wheel operating pinion, S′, for regulating electrodes by hand; R, rack gearing with S, by which electrode is raised or lowered. An alternating current at 110 volts is used.

for melting and refining some lime and iron ore are first placed upon the furnace bottom, and then miscellaneous wrought iron and steel scrap, such as old bolts, plate cuttings, &c., are charged into the furnace, and the electrodes are lowered sufficiently to establish an electric circuit, the current passing between the electrodes and the charge. At first, before the iron is melted, the electrodes are generally in contact with it, and numerous small arcs and high resistance contacts are formed between the pieces of metal, which largely absorb the energy of the current. The resistance of the charge varies greatly during this period, violent fluctuations of the current taking place owing to the continual change in contacts and disruption of circuits, but gradually, as the metal melts and an arc is established between each of the electrodes and the molten bath, the greater part of the energy is absorbed by these two arcs. When the bath is melted, the electrodes are kept just above the surface of the slag, the width of the air-gap being controlled by the regulator. Iron ore and lime are added from time to time exactly as in the ordinary open hearth process, and when the bath of metal and slag is completely melted the current is switched off.

The furnace is then tilted, and the slag poured off; to remove the slag completely, the surface of the metal is skimmed with an iron rabble, the slag being raked off the bath through the door over the pouring spout. A new slag is now formed by adding lime and fluorspar and a little ore, with sufficient sand to give fluidity, and the current switched on to melt it completely. After the slag has been melted for some time, it is poured off, and the surface of the bath again raked to remove it as completely as possible; further additions of lime, fluorspar, &c., are then made to form a finishing slag, to remove the last traces of impurity. In the case of dead soft steel, after the slag has been poured off, from 1·0 to 1·5 lbs., and in some cases as much as 2 lbs. of 80 per cent. Ferro-Manganese per ton of steel is added in the furnace, and the metal is poured into the ladle and teemed into ingot moulds, a little Aluminium being added in the ladle. When high Carbon steel is required "carburite," a mixture of pure Carbon and iron, is added until the required degree of carburisation is obtained, and also about 10 lbs. of 12 per cent. Silicon pig per ton of steel. The bath is sampled in the usual way with a spoon ladle, and when the furnaceman is satisfied with his sample the metal is poured into the ladle and teemed. The time from charging to tapping varies from about six to eight hours, according to the grade of steel required.

It will be noted that when starting with scrap iron the first product obtained is soft steel; to produce high Carbon steel, the bath of soft steel first obtained has to be carburised by suitable additions. Consequently, the metal has to be kept longer in the furnace to produce high Carbon steel than low Carbon steel, and the consumption of electric energy is greater in the former case than the latter. This is just the reverse of the Kjellin practice, where it takes longer to produce dead soft steel than it does high Carbon steel. The method of working, however, depends more upon the materials commercially available than anything else, and there would be no difficulty in making high Carbon steel without recarburising by melting down a suitable mixture of pig and scrap in the Héroult furnace; and, on the other hand, pure scrap could be melted down in the Kjellin furnace and recarburised by suitable additions at the end of the operation if desired.

The amount of energy required for melting and refining cold scrap to produce 1·00 Carbon steel varies from 700 to 1,000 kilo-watt hours, according to the capacity of the furnace. About 110 tons of scrap are required to

produce 100 tons of ingots. The cost of repairs and renewals, when melting and refining cold scrap, including roof and basic and acid refractories, varies from 3s. 6d. to 5s. 6d. per ton, according to the price of materials in different places, and the output of the furnace. A Héroult furnace at La Praz of 2·4 tons capacity made twenty consecutive heats, melting and refining common scrap at the rate of about four heats per twenty-four hours, of which five hours ten minutes was the average duration of the heat, and the average intervals for fettling and charging were forty minutes. The yield of ingots was 94 per cent. of the rough scrap charged, and the consumption of electricity was 765 kilo-watt hours per ton.

Recently there have been considerable developments in the direction of the refining of molten Bessemer or open hearth steel, the steel being conveyed to the furnace in a ladle and subjected to a refining by addition of suitable fluxes, one or more slags being made according to the degree of purification required. The energy consumed under these conditions varies from 120 to 300 kilo-watt hours per ton of steel produced, according to the quality of steel required. In the case of five consecutive heats at one of the furnaces used by the United States Steel Corporation for refining steel from an acid Bessemer converter which was high in Phosphorus and Sulphur, the consumption was 172 kilo-watt hours per ton, and when producing the same quality of finished steel from open hearth metal low in Phosphorus the consumption of energy fell to 111 kilo-watt hours. The cost of refractories, renewals, &c., is very considerably reduced when molten metal is used instead of cold scrap. The Silica brick roof is stated to last from 100 to 150 heats, and the total cost not to exceed sixpence to one shilling per ton, according to capacity, &c., of the furnace.

The following may be taken as a typical analysis of the steel produced, the Carbon being varied as required :—

Carbon,	0·060 to 1·700
Silicon,	0·080 to 0·180
Sulphur,	0·013 to 0·022
Phosphorus,	0·009 to 0·012
Manganese,	0·140 to 0·270
Arsenic,	trace to 0·09
Copper,	trace

The arsenic and copper will vary with the percentage present in the raw materials used, as these impurities are not removed during the working of the charge. From a number of analyses made of Héroult and Kjellin steels by the author for the Canadian Government Commission from the centre, the top, and the bottom of different ingots, both steels were shown to be of very regular composition, and remarkably free from the segregation of impurities. The mechanical properties of both steels were extremely good, and when forged into tools and compared by series of trials in the lathe with the best crucible tool steel of similar content of Carbon, they gave results in every way equal to their more costly competitor. The above results have been fully confirmed by further experience, and now there are a number of these furnaces, both in Europe and England and America, either in operation or in course of erection.

Special steels, or high-speed tool steels, are now being made commercially in the Héroult furnace, and there is no reason why such steels should not be satisfactorily and economically produced in this and other electrical furnaces.

THE KELLER PROCESS.

The original furnace employed really consisted of two furnaces at different levels, one fixed and one tilting. When working pig and scrap, the materials were melted and partially refined in the upper furnace, and then tapped into the lower tilting furnace, where the charge

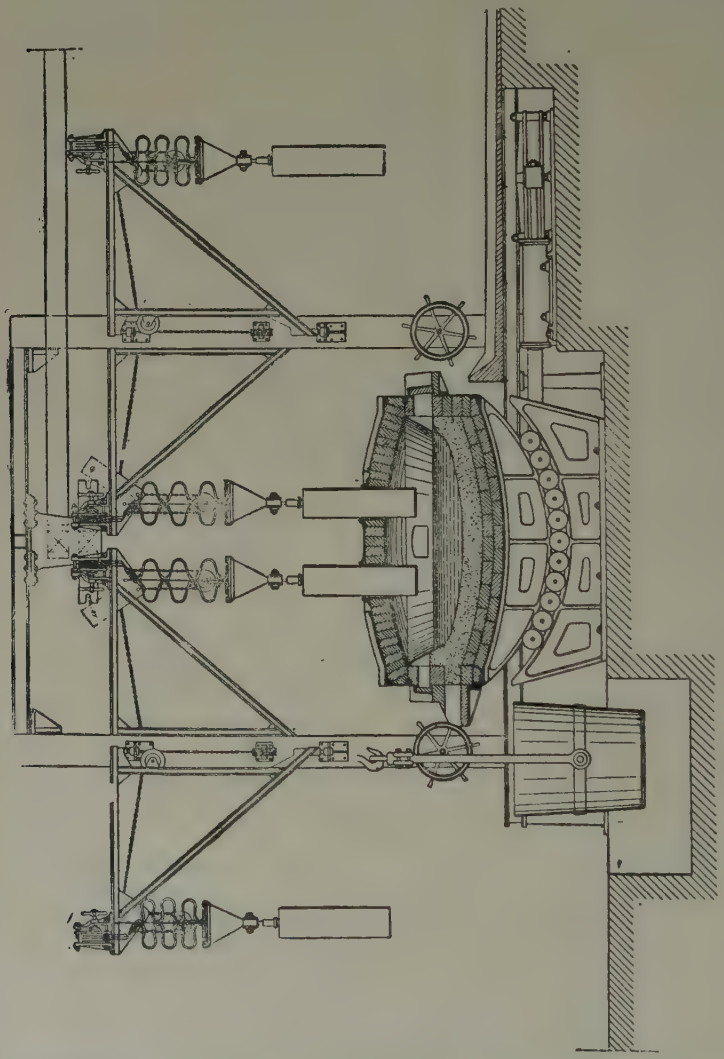


Fig. 198.—Sectional Elevation of the Keller Furnace.

was finished. Care was taken that the slag from the melting furnace did not pass into the finishing furnace with the metal. When working scrap charges, the preliminary refining furnace was dispensed with, and the scrap was melted direct in the tilting furnace; this latter furnace was mounted on trunnions, and could be tilted in either direction. Instead of having a spout, it had a tap hole at one end, and not in the centre of one of the

longer sides, as is usual in open hearth furnaces; at the other end was a slag hole. The metal was tapped out in the usual way, the furnace being tilted to drain all the metal off. During the working of the charge, slag was poured off several times from the slag hole at the opposite end to the taphole by tilting the furnace in that direction; the furnace was basic lined.

The electrodes passed through the roof and were regulated by hand, and the charge was melted down with lime and ore additions exactly as in the Héroult process, the slag being poured off and a new slag formed two or three times during the operation; the details of working being the same as in the Héroult process, it is not necessary to repeat them.

Since the original furnace was erected the design has been considerably modified, the latest type erected at the Holtzer Steel Works, Unieux, France, being mounted on rollers for tilting. The body of the furnace is circular, and there are four electrodes mounted on movable supports independent of the furnace, so that they can readily be removed and replaced when necessary. The electrodes pass through the roof of the furnace, and two electrodes in parallel are coupled to each pole. The current is regulated by raising or lowering the electrodes by motors, and each electrode can be manipulated independently. This particular furnace is used for refining molten metal, but it is equally well adapted for the use of cold scrap. Fig. 198 shows the general design of this furnace and method of supporting the electrodes.

Steel of any Carbon content from 0·08 to 1·5 per cent. or higher, and extremely low in Sulphur and Phosphorus, can be made. From a metallurgical standpoint, the process is identical with the Héroult process, working under similar conditions, and the same high quality of products can be obtained.

THE GIROD FURNACE.

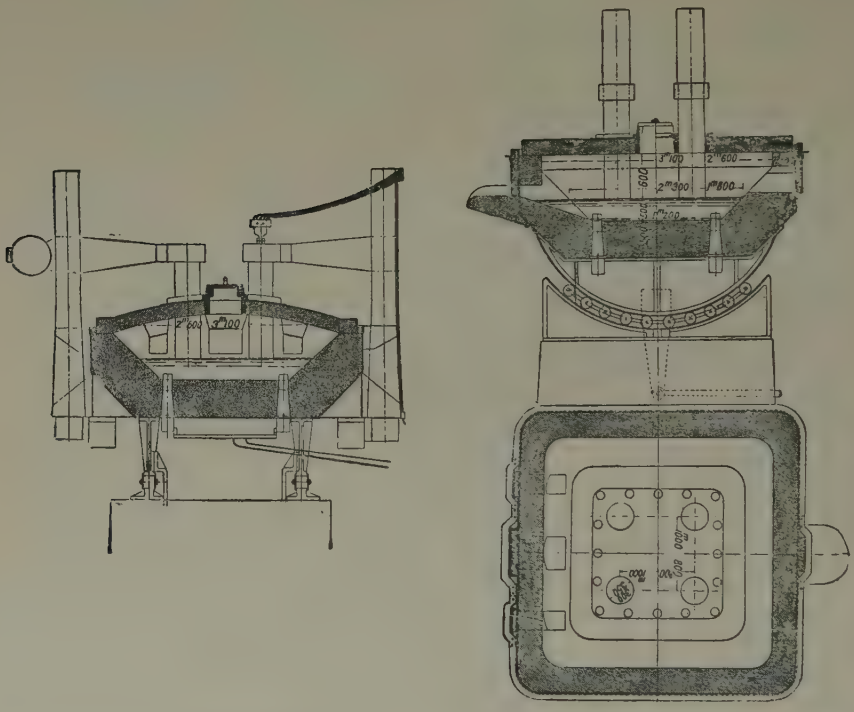
A sketch of this furnace is shown in Fig. 199, and in general construction it is very similar to the Héroult furnace, but it differs in that the electrodes passing through the roof are of like polarity, and pole pieces of soft steel embedded in the hearth of the furnace and in direct contact with the molten metal form the negative electrode. The current enters by the upper electrodes, forms an arc between itself and the bath, traverses the bath, and passes out through the lower pole pieces. These lower pole pieces have a cavity about 6 inches deep on their lower ends, which are water-cooled, and notwithstanding the fact that the upper ends in contact with the bath become molten, not more than a few inches are said to wear away during several months' work.

In small 2-ton furnaces a single electrode through the roof is used, but in larger furnaces several electrodes may be used, but whatever their number they are all mounted in parallel and connected with the same terminals of the machine, the other terminal being connected with the metallic pole pieces.

At the Oehler Works, Aarau, Switzerland, a 2,000-volt two-phase current system supplies a 450 H.P. motor, running at 560 revolutions, and is coupled direct to a single-phase alternator, giving 4,600 to 5,000 amperes single-phase current at 65 to 75 volts, the frequency being 37·4 periods per second. Twelve heavy copper cables, each 0·8 in. diameter and composed of twelve copper wires twisted together, carry the current to the furnace. The voltage drop is 2·5 volts from the machine to the furnace. The furnace is 6 feet 8 inches diameter, 20 inches high inside, and is electrically tipped and regu-

lated. The electrode passing through the roof is automatically regulated so as to keep the current at the desired strength by an automatic regulator designed by R. Thury, of Geneva. The electrode is 14 inches square by 60 inches long, and weighs at starting 440 lbs., and lasts, on an average, from five to seven charges.

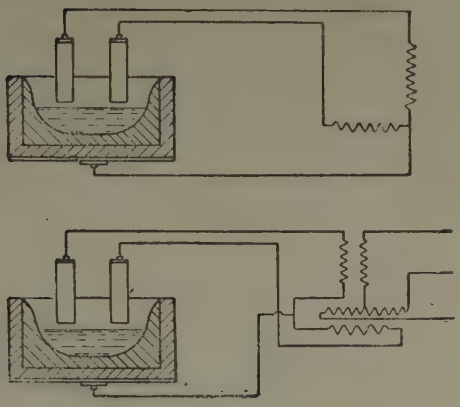
The usual charge consists of steel and cast-iron scrap and turnings, with some pig iron, and each charge takes from five to six hours after charging to finish completely.



Sectional Elevation. *Plan and Sectional Elevation through pouring spout.*

Fig. 199.—The Girod Furnace.

The furnace is basic lined, Magnesite being generally used for the hearth, and the roof is as usual made of Silica brick. The smaller furnaces are used principally for the manufacture of steel castings, but large furnaces up to 12½ tons capacity are being used at Ugine. The advantages claimed for this furnace are that the current can be easily regulated automatically owing to there being only one fall of tension to be regulated; that the low voltage, about 50 to 55 volts, renders it easy to insulate the electric conductors thoroughly; and that the current passing through the metal bath, the entire mass is traversed by the current, and almost the whole of the difference in voltage at the terminals of the furnace is absorbed by the resistance of the charge, which is of special advantage during the melting down period. Either a continuous or an alternating current can be used,



Figs. 200 and 201.—Electric connections to Grönwal Furnace.

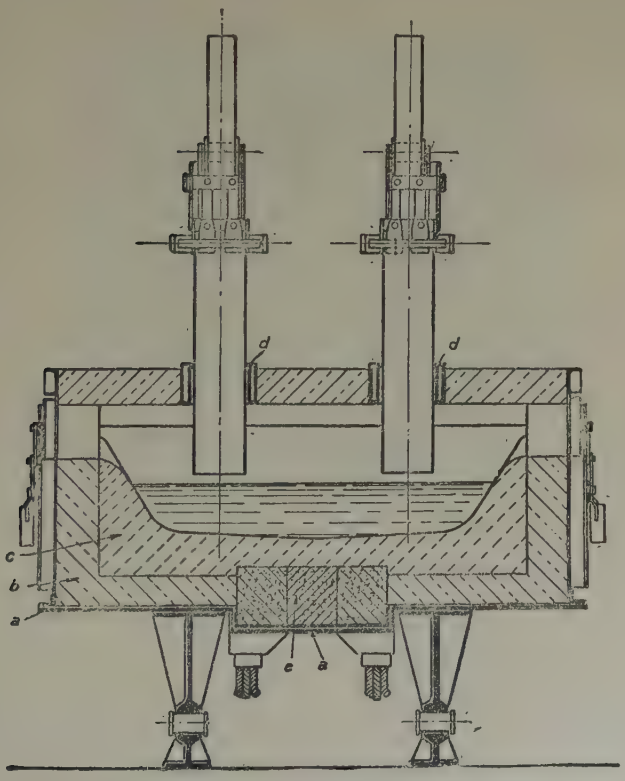


Fig. 202.—Grönwal Furnace—Longitudinal Section.

a. Cast-iron plates.
b. Layer of Graphite or Carbon.
c. Basic material or Magnesite.
d. Water-cooled blocks round electrodes.
e. Solid Carbon block embedded in the lining.

THE GRÖNWAL FURNACE.

This is another electrode or arc resistance furnace designed to employ a two-phase current instead of a single-phase or three-phase current, which has been introduced in Sweden. The furnace is mounted on a tilting frame the same as a Héroult or Keller furnace. It is built up on cast-iron plates, a layer of Graphite or Carbon of high conductivity being placed upon these, and upon this the basic material to form the hearth; solid Carbon blocks are embedded in the bottom lining as shown in the sketch, Fig. 202. The advantages

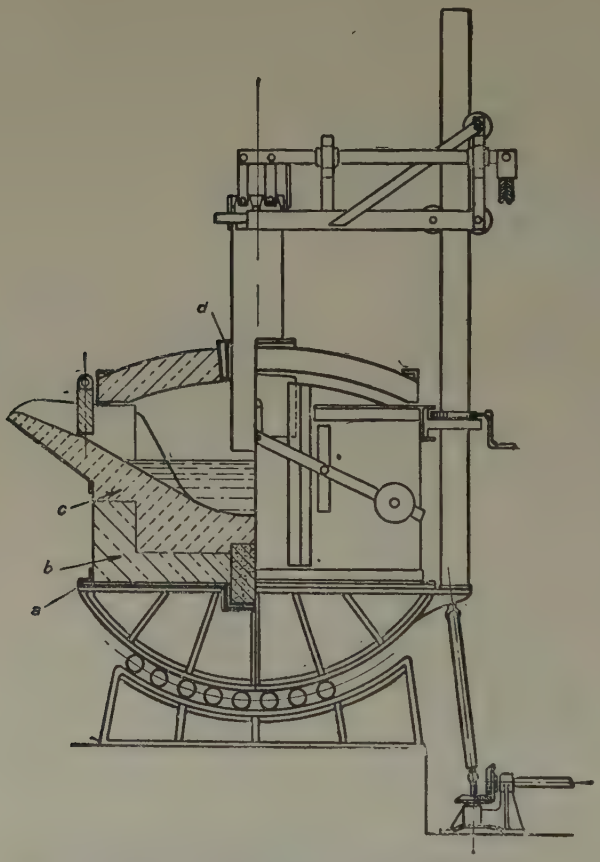


Fig. 203.—Grönwal Furnace—Cross Section.

claimed for this two-phase arrangement are that the generating plant and transmission are cheaper and more satisfactory in operation; that a three-phase current can be generated and transmitted, and transformed into two-phase in the furnace room; that the heat is transmitted through the charge, and stirs the metal up from the bottom of the furnace and the circulation of the bath is more complete; and that the two arcs not being in series but separate phases, are independent of each other, and can be regulated separately, so that the control of the current is more complete.

Fig. 200 shows diagrammatically the electric connections for an ordinary two-phase current, and Fig. 201 the arrangement for transforming the three-phase into a two-phase current. Fig. 202 is a vertical longitudinal section of the furnace, showing details of Carbon sole, &c., and Fig. 203 shows furnace in cross section, method of tilting, &c.

From the metallurgical standpoint this furnace is identical with other arc furnaces, and the operation of melting and refining is exactly the same. Whether the Carbon sole will give satisfactory results in practice can only be determined after the furnace has been in operation for a considerable period.

THE RUTHENBURG FURNACE.

An experimental furnace of this type has been erected at the works of the Brush Company, Loughborough, and although up to the present it is not installed in any works producing steel commercially, it has several novel features of considerable interest. It is a resistance furnace using a three-phase alternating low-tension current, and the ends of the electrodes are

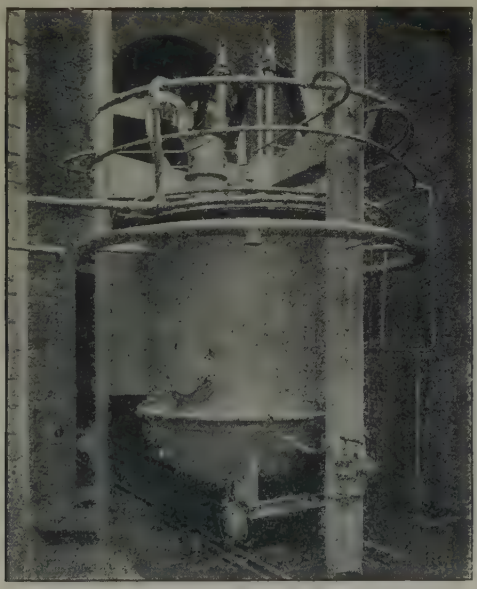


Fig. 204.—Ruthenburg Furnace.

immersed in the slag, which acts as a resistance, and consequently becomes heated to a high temperature. The body of the furnace consists of a circular iron casing lined with refractory material provided with doors for charging, &c., and with a movable bottom mounted on a carriage or bogie, so that it can be readily withdrawn from the furnace body and replaced by another, thus facilitating repairs, and enabling the furnace to be kept in continuous operation during the relining of the hearth; the bottom is withdrawn for casting the metal, but in regular work it is doubtful if this would be practicable, and it is probable that better results would be obtained by

mounting the furnace on a tilting frame, and pouring the metal into a ladle and teeming in the usual way. The electrodes are vertical, and pass through the roof, the special feature being that they are water-jacketted to *within a few inches of the bath;* these jackets are lined with a refractory material. The water-jacket largely protects the electrodes from the action of any furnace gases generated and air which leaks into the furnace, and enables the Carbon electrodes to be fed through the jacket, so that the whole of the electrode can be used, thus resulting in considerable economy in electrodes. The consumption of energy is apparently about the same as in other resistance furnaces producing steel from similar materials, but this point, and also the actual saving in electrodes, cannot be accurately determined until detailed results from a furnace running continuously over a period of some months are available. The furnace is also suitable for manufacture of alloys, and numerous experiments have been made in smelting different classes of ore. Fig. 204 illustrates the general design of the furnace.

THE GIN FURNACE.

This is a resistance furnace designed to avoid the disadvantages attending the use of electrodes, and it depends upon the resistance offered by a bath of molten steel of small cross-sectional area.

The furnace hearth consists of a trough or channel of considerable length and small cross-section; this channel is filled with molten pig-iron, and terminal water-cooled blocks are provided for connections for the electric circuit. For convenience, the channel which holds the metal is doubled upon itself several times, so that in plan it has the form of a huge filament of an incandescent lamp. By varying the current passing into the fused metal the required temperature can be obtained. It is stated that by having the terminal blocks of very large section in comparison with the section of the channel carrying the molten metal, and by internal water-cooling, they are prevented from attaining a very high temperature. The furnace is basic lined, and can be used as a crucible or melting furnace for the production of steel, by melting selected pure materials to give the composition of steel required, or it can be used with pig and scrap, additions of ore, lime, &c., being made in the usual way to effect the oxidation and removal of impurities. The difficulty of charging the pig-iron, scrap, ore, &c., into such a furnace during the working of the charge, and the maintaining of the hearth or channel in fair repair, seems to rule out a furnace of this design for the manufacture of steel on anything like a commercial scale, and so far it has not been a success.

A combined form of induction and arc furnace was described by Gin at the meeting of the American Electro-chemical Society at Niagara in May, 1909, in which there were two reservoirs heated by arcs and united by tubular channels inclined in opposite directions, one of which was heated by induced currents from primary and secondary windings, and the other formed with the two reservoirs, the secondary circuit. So far as one could judge from the description there would be considerable difficulty in repairing these canals or channels, and the furnace, from a metallurgical standpoint, does not appear to offer any special advantage over the other types which have proved satisfactory in practice.

THE GIFFRE FURNACE.

This furnace differs from those resistance furnaces already described, in that only one of the electrodes passes through the main roof of the furnace into the hearth of the furnace, and the other electrode is contained in a separate chamber built on to the main body of the furnace, and the electrical connection is maintained by a narrow channel of molten metal between the two electrodes. One advantage of this form of furnace is that structurally it is stronger than the Héroult type, as the roof is not weakened by two electrodes passing through it, and, further, there is no danger of any short circuiting of the current between the two electrodes. The furnace is a resistance furnace, the channel of molten metal being maintained in the fluid condition by the resistance it offers owing to its small cross-sectional area. So far as the author is aware, this furnace has been used exclusively for the production of Ferro-Alloys, and has not been used for steel making or refining, although there seems no reason why it should not give good results in this direction. Comparatively little, however, is known about the details of construction or methods of working this furnace, as nothing has been published, and the patentees are somewhat reticent about giving any particulars. It has, however, been very successfully employed for the manufacture of alloys, especially Ferro-Alloys, low in Carbon like very rich Ferro-Manganese, Tungsten, Molybdenum, &c., containing less than 1 per cent. of Carbon.

THE STASSANO ARC FURNACE.

In this type of furnace the necessary heat is obtained by direct radiation from the arc and by reflection from the roof and sides of the furnace. As far back as 1879 the late Sir Wm. Siemens designed a small crucible furnace capable of melting a few pounds of steel on this principle, and the Stassano furnace is the best known furnace of this type used for the smelting of iron and steel. It is shown in Fig. 205, with a description attached. The furnace rotates round an axis inclined about 7° to the vertical. In one modification of the furnace it is mounted on a tilting frame, the rotation being dispensed with. There are three electrodes, which nearly meet in the centre of the furnace, their distance being regulated by hydraulic rams. A three-phase alternating current is used and distributed between the three electrodes.

The furnace is capable of producing 4 or 5 tons of steel per day, a current of 4,900 amperes at 150 volts being distributed to four electrodes supplying two arcs with 2,450 amperes for each arc. The electrodes are cylindrical in shape, about 6 inches in diameter, from 50 to 60 inches long, and weigh about 132 lbs. The furnace is lined with Magnesite blocks made specially to the shape of the furnace, the roof also being built of Magnesia bricks. The weak point about this type of furnace is the cost of repairs, the direct radiation from the arc on to the roof being very destructive; the life of the roof might probably be considerably prolonged by slight modification in design, and possibly Silica bricks may be used, but so far as present experience goes no refractory material except Magnesite bricks have been found capable of withstanding the high temperature, and the cost of these is considerable.

This furnace is doing very good work in the manufacture of steel castings of extremely soft quality from miscellaneous iron and steel scrap. The scrap, mixed with a little oxide of iron and lime, is charged and melted down as usual, and towards the end of the operation a portion of the slag is poured

or raked off and a fresh slag formed by suitable additions to reduce the Phosphorus to the required extent and desulphurise the bath. For small charges of about 1 to 2 tons, especially when the metal has to be poured into a number of small moulds, this furnace is particularly suitable, the fluidity and purity of metal enabling very sound castings of highest quality to be produced.

Various experiments have been made in this furnace to produce steel direct from the ore, and with exceptionally pure ores very promising results have been obtained, but owing to the difficulty of controlling the composition of the slags with average ores, the production of steel of any required grade is far from easy, and the wear and tear on the furnace is so considerable that

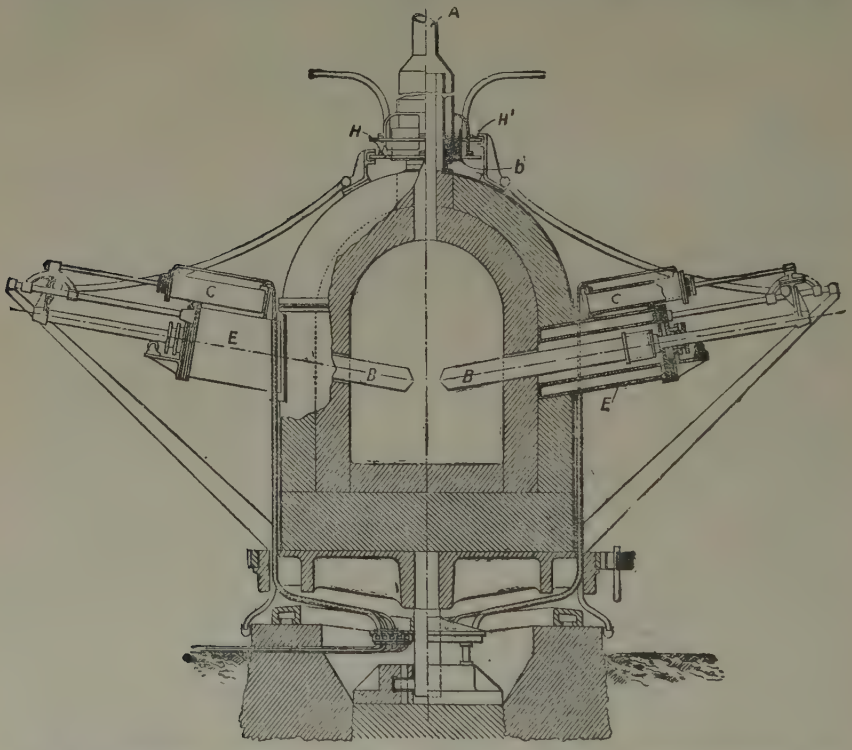


Fig. 205.—Sectional Elevation of Stassano Electric Furnace.—Furnace lined with Magnesite bricks. The furnace is slightly inclined to the vertical, and rotated by mechanism, shown below. Volatile products led off through tube, A. B B, Electrodes; C C, hydraulic cylinders for regulating electrodes; E E, water-jacket for electrodes; H H', two strong metal insulated rings (fastened to fixed tube, *b*, which does not rotate with furnace) to receive current from cables. The current is conducted to the electrodes from these rings by means of brushes, which run along the rings with the movement of the furnace; the electrodes rotate with the furnace. There is a tap hole for metal at bottom of furnace, and a slag hole at somewhat higher level. The charge is fed through a hopper and inclined shoot to deliver below the electrodes.

there does not seem any probability of this being commercially successful; in any case a large amount of experimental work will have to be done before the commercial stage is reached.

The Removal of Phosphorus and Sulphur.—Under proper conditions the elimination of Phosphorus and Sulphur from the metallic charge in the electric furnace is far more complete than in the open hearth or any other process of steel manufacture. If we except the Kjellin induction furnace, all types of electric furnaces may be regarded as basic open hearth furnaces, in which refining can be carried on at a much higher temperature, and in which a nearly neutral or non-oxidising atmosphere can be maintained during the whole operation. So far as the removal of Phosphorus is concerned, the slightly oxidising slag, combined with its high basicity and the fluidity which can be maintained by the high temperature, is sufficient to explain its complete removal, and to some extent the same applies to the removal of Sulphur, but it does not entirely account for the latter. It is well known in basic open hearth practice that Sulphur, especially when it is desired to remove it to below ·05 or ·04 per cent., cannot be eliminated until the end of the operation, and the necessary conditions are a non-oxidising basic fluid slag; the lower the percentage of oxide of iron and the higher the percentage of lime the more completely is the Sulphur removed. The elimination, however, is limited by the difficulty of maintaining a highly basic slag of sufficient fluidity, free from oxide of iron, and, further, by the fact that Sulphur is liable to be taken up from the gases in an oxidising atmosphere and oxidised into Calcium Sulphate, when it may pass again into the bath of metal according to the equation—

$$CaSO_4 + 4Fe = FeS + 3FeO + CaO.$$

The Sulphur in the metal is present as Sulphide of Iron dissolved in the steel, and its removal in combination with Calcium as Calcium Sulphide is not an oxidising reaction like the removal of Phosphorus, but a reaction taking place under reducing conditions; hence the presence of a reducing agent facilitates, while the presence of oxides of iron retards its removal.

The removal of Sulphur in the Héroult furnace has recently been investigated by Dr. Th. Geilenkirchen,* and he explains it as due to the action of the Carbide of Calcium formed in the slag, which by its reducing action first deoxidises the metal and reduces the oxides in the slag, and then removes the Sulphur according to the following equation:—

$$2Ca + 2FeS = 2CaS + 2Fe.$$

To facilitate the reduction of oxides and obtain a neutral slag, the usual practice is to throw small quantities of powdered Carbon on the top of the slag on which it floats, and while rapidly reducing the oxides in the slag, does not pass into the metal.

In the Héroult or similar type of furnace, the high temperature enables slags of almost any degree of basicity to be maintained in a state of fluidity, and slags containing 63 per cent. to 65 per cent. of lime and 1 per cent. of iron are not uncommon; the atmosphere is practically neutral and there can be no doubt that Carbide of Calcium is produced in the slag, so that we have all the conditions essential to the removal of Sulphur, and the above explanation seems to accord with the facts.

Although the above may explain the Sulphur removal in electrode resistance furnaces it cannot be suggested that Carbide of Calcium is formed in the induction furnace, and as the removal of Sulphur is equally complete, the conditions of its removal require a little consideration.

* *Stahl und Eisen*, July 15, 1908.

Prof. Osann * has very carefully investigated this question, and he at first tried to remove the Sulphur by an extremely basic slag thinned with fluorspar; but this was not successful to the extent required, and he soon found to reduce the Sulphur to ·01 per cent. or less it was necessary to add some powerful reducing agent to remove the oxides in the slag. In the first case Carbon was added to carburise the metal and reduce the oxide of iron in the slag, but this was not found to be efficient, and finally small quantities of 50 per cent. Ferro-silicon were added to the slag. The method of procedure is as follows:—After the removal of Phosphorus, the slag is poured off as completely as possible and a new slag made with lime and fluorspar. Ferro-silicon, in pieces the size of an egg, is added in sufficient quantity to give about ·35 of Silicon in the bath, and then small quantities of Ferro-silicon broken to the size of peas are thrown into the slag until it is white and shows by its colour on sampling that it is free from iron, by which means the Sulphur can be reduced from ·06 or ·07 per cent. to ·008 per cent. The use of Ferro-silicon has the advantage that its oxidation at the expense of the oxide of iron produces heat, and raises the temperature of the hearth. The reducing conditions may be assisted by additions of Carbon powder as well as Silicon.

Prof. Osann considers the presence of oxide of iron in the slag prevents desulphurisation, because of the reaction $FeO+CaS=FeS+CaO$, which is a strongly exothermic reaction, or reaction attended with considerable evolution of heat. It is of considerable interest to note that two quite independent investigators working under different conditions have both arrived at the same conclusions as to the essential conditions for desulphurisation; although the particular means employed to produce these conditions were different in each case, the results obtained are very largely confirmed by ordinary basic open hearth experience, and, in the author's opinion, there is little doubt as to the general soundness of the deductions drawn.

It must be remembered that the addition of reducing agents to the slag is only possible after the removal of the phosphoric slag, as otherwise the Phosphorus would be reduced and pass into the metal, and hence it would be difficult to apply these methods of desulphurisation in the basic open hearth process as worked under ordinary conditions with a highly Phosphoric slag.

Manufacture of Steel in Different Furnaces.—It is extremely difficult to compare the cost of production in the different furnaces described, as to obtain reliable results it would be necessary to carry out an exhaustive series of experiments with each furnace, working under identical conditions as to supply of raw material, &c., but so far as the consumption of energy is concerned for the production of the same grade of steel, there is probably no very great difference, and the advantage claimed by one furnace over another in this respect is probably due more to some variation in materials used. size of furnace, &c.; than to the difference in electrical efficiency. That there is some difference in this respect must be admitted, but this taken alone is hardly likely to be a determining factor in the selection of a furnace, and other considerations, such as the facility with which a furnace can be charged and tapped or repaired, and similar practical considerations, are likely to carry far more weight with the steel maker.

In starting with cold materials, such as steel scrap and pig, the consumption of energy per ton of steel produced may be taken as from 850 to 1,000 kilo-watt hours, according to the grade of steel produced and the size of the furnace, as in larger furnaces the energy consumed per ton of steel

* *Stahl und Eisen*, July 17, 1908.

is less. The cost of refractories will vary considerably with the size of the furnace and the price of the materials delivered at the works, but probably a fair figure is 5s. to 6s. per ton for small furnaces under ordinary conditions, although in steel-making districts in England this might be somewhat less. The consumption of electrodes will also vary somewhat with the type and size of the furnaces; in the Héroult furnace, about 35 lbs. being used per ton of steel produced, and in the Girod about the same, whereas in the Stassano arc furnace only about 20 to 22 lbs. per ton of steel is stated to be consumed.

Where pure materials can be procured, as in Sweden, and pure scrap and pig iron can be mixed together in such proportions as to give a steel of the required composition, the original Kjellin induction furnace has much to recommend it, as we are able to obtain practically all the conditions of crucible melting with the additional advantage that tons can be melted down instead of pounds.

If, on the other hand, the raw material is ordinary miscellaneous scrap, then it is absolutely necessary to have a furnace in which extremely basic slags can be retained in a state of fluidity to refine the metal, and that these slags can be removed when desired, and additions of basic materials added to form new slags to purify the steel completely; in such cases we have to select either an arc resistance furnace, like the Héroult, Keller, or Girod, an arc furnace like Stassano, or the new Roechling-Rodenhauser induction furnace. All these furnaces are capable of making steel of the highest quality from common scrap, and the high temperature obtainable and freedom of steel from oxidation give exceptional fluidity to the metal which is particularly suitable for the manufacture of sound castings; all these furnaces have been very successful in the production of castings from practically dead soft steel.

At best the electric furnace is a dear melter, especially in England, where the cost of producing electric energy must always be comparatively high; but it is an economic refiner at those high temperatures, when the reaction between the slag and the metal is most effective. It is, therefore, as a refiner for ordinary steel that the electric furnace is deserving of most careful consideration.

The consumption of energy in refining molten metal is practically the same in all types of furnace, but will vary according to the quality of the finished product required, from 120 to 300 kilo-watt hours per ton of steel produced. In Germany and the United States, where furnaces are being used for refining basic and acid Bessemer metal for the production of higher-class rail steel, from 100 to 150 kilo-watt hours per ton are required, but for better-class steel 250 to 300, and in case of special tool steels as much as 350 kilo-watt hours per ton of steel have been found necessary.

In England it seems doubtful if the electric furnace will be largely used for rail steel manufacture, as the quality of steel produced from our acid and basic open hearth furnaces and converters gives generally satisfactory results, and it is a question whether the improvement in quality would necessarily give such results in service as would justify the increased cost.

In America the position is somewhat different, as a large proportion of their Bessemer ores cannot produce rails with less than ·10 per cent. of Phosphorus, and to meet the more severe requirements of modern specifications steel makers will either have to scrap their existing Bessemer plants and erect some form of basic open hearth furnaces or adopt some refining method for removing the Phosphorus in their blown metal. The United States Steel Trust have recently erected several 15-ton Héroult steel furnaces

to work in conjunction with their Bessemer plants, for refining the blown metal for rail steel, and the results are stated to be very satisfactory, and it is probable other furnaces will be erected.

Apart from the manufacture of high-class crucible steel and steel castings, for which there is a comparatively small demand, and steel rails, for which there is a very great demand, there are many intermediate products between these, for which a high-class steel is required, such as axles, tyres, special forgings, &c. All these could be produced by refining molten metal from an open hearth furnace or Bessemer converter at a cost which in many cases would compare very favourably with present costs in the open hearth furnace. Practically for all these steels specially selected pig-iron and scrap has to be used, for which high prices have to be paid, whereas if the electric furnace were used as a refiner the ordinary quality of Bessemer pig-iron and common scrap could be employed, and the decrease in cost of materials would probably quite meet the costs of refining, with the additional advantage that there would be an improvment in the general quality and regularity of the finished steel. Except for the highest class of steel products, the electric furnace cannot hold its own when using cold materials, and it is as a refiner for Bessemer and open-hearth steel that its future development is likely to take place.

It must be remembered that refining is not simply a question of producing a steel of better chemical composition lower in Phosphorus and Sulphur, but the steel is maintained fluid in a neutral atmosphere out of contact with all gaseous products of combustion, and the conditions are such that there is every opportunity for the escape of occluded gases, and for the almost complete deoxidation of the steel. Both deoxidation and the removal of occluded gases are recognised by practical steel makers to have a most important influence on the physical properties of steel, and it is probable that the special qualities of steel made in the electric furnace are largely due to its freedom from oxidation and occluded gases.

General Conclusions.—The present position which the manufacture of steel in the electric furnace holds in relation to other processes may be briefly summed up as follows:—(1) That steel of the highest quality equal to the best crucible steel can be made in this country either from cold scrap or by refining molten open hearth or Bessemer steel in any of the well-known types of furnaces at a price less than it costs to make crucible steel. (2) That steel castings of highest quality, especially when required very small and of light section, can be made at lower cost and equal in every way to best crucible steel castings. (3) When steel of high class quality, such as axle, tyre, and steel for special forgings, is required, such as only can be made from very carefully selected high-priced materials, under favourable conditions, the electric furnace can compete with the open hearth furnace, especially if molten metal from a Bessemer converter or open hearth furnace is available for refining; the cost of refining in such cases is compensated for by the lower cost of the raw materials; no generalisations, however, can be made, each case must be considered independently when all the facts are known. (4) In the present state of development of the electric furnace it cannot compete as regards cost of production with a modern large open hearth furnace or Bessemer plant for the manufacture of rails and structural steel for ordinary purposes, and it is only when superior quality is required, for which a better price can be obtained, that it can be employed.

In the great majority of cases Bessemer metal or, at all events, open hearth steel is good enough for rails, and it is only in cases where the raw

materials are such that there are difficulties in obtaining the low Phosphorus and Sulphur demanded by modern requirements, as is the case with much of the American Bessemer steel, that the electric furnace will be used for rail manufacture, unless experience should demonstrate that the life of such rails is so increased as to justify the cost of this refining.

The future development of electric steel manufacture, apart from the manufacture of tool steels and steel castings, will probably be in the direction of the manufacture of the intermediate high-class steels for axles, tyres, guns, and similar purposes, replacing the material at present made from selected high-priced pig-iron in the open hearth furnace; the furnace will not be used for melting cold materials, but in refining molten metal from open hearth furnaces or Bessemer converters. When an open hearth plant is desired, the Talbot process or some form of open hearth tilting furnace will be necessary for the best form of combination plant, and the facilities for a continuous supply will then be similar to those from a Bessemer plant, although probably results equally good as regards quality can be obtained from the latter.

Much depends upon engineers being able to design electric furnaces of from 30 to 40 tons capacity, and so reduce the costs incidental to the working of small furnaces. Provided the difficulties can be overcome with large electrical furnaces, as they have been with gas-fired furnaces, the future of the electric furnace worked as a refiner of molten metal is assured for the manufacture of high-class steel in large quantities, and it will prove a powerful competitor to the open hearth process producing steel direct, and the greatest possibilities of development are probably in this direction.

Some of the sketches in this chapter are reproduced by permission from "The Report of the Canadian Commission appointed to Investigate the different Electro-Thermic Processes for the Smelting of Iron Ores and the Manufacture of Steel in operation in Europe." The horse-power year is taken, in all cases, as 365 days of 24 hours.

CHAPTER XII.

ARMOUR PLATE MANUFACTURE.

This branch of the steel industry involves several metallurgical processes peculiar to itself, and has now assumed such large proportions that it is of sufficient importance to merit special notice.

Varieties of Armour Plate.—Armour plates as a rule belong to one of two classes—namely, compound armour plates, and face-hardened armour plates—each type being made by several more or less different processes. In all cases the object aimed at is the production of a plate which shall be sufficiently hard to prevent its being pierced by the shot, and at the same time of such toughness that it will not crack or break.

When armour plates were first made, they consisted simply of plates of wrought-iron, and the first great improvement was the adoption of the compound armour plate, which was made up of a soft iron plate united to a face-plate of hard steel. In 1888 the first British all-steel plate was made by Messrs. Vickers with very satisfactory results, and not long afterwards plates made entirely of nickel steel were introduced.

One of the most important improvements in armour plate manufacture was Harvey's invention of a method of face-hardening mild steel plates, by what is known as Harveyising, which consists of carburising one side of a mild steel plate by a process akin to that of cementation, while the other side is allowed to remain in its original condition, or is decarburised by Oxide of Iron; the carburised side is afterwards hardened by sudden chilling with water. Of other methods of face-hardening, Krupp's process is perhaps the most important.

Modern armour is universally made of one or other of the ferro-alloys, usually Nickel-Chromium, low in Carbon, with small percentages of Manganese, Tungsten, &c.; the proportions are usually considered a trade secret, and in all probability vary with the thickness of the plate. Plates may be cast up to 6 or 7 inches in thickness, and may or may not be cemented. Cementation enables a glass-hard surface to be obtained without affecting the tough qualities of the remainder of the plate, and seems to give the best results with a 6-inch plate, the hardening effect extending about 2 inches inwards, gradually diminishing from the outside, and the 2 to 1 proportion between the tough back and the hard face represents good practice. It has been found that the steel for cemented and water-hardened face armour must be much more carefully selected and treated than that for the early chilled armour, and it is very important that the plate should gradually grade from the hard face to the soft back, otherwise under attack the skin flakes off or cracks.* Most makers object to the cementation of thin curved plates, as warping or cracking is likely to result. Krupp, however, claims to have solved the problem of manufacturing curved plates, possessing all the features of best Krupp armour.†

Below 4 or 5 inches in thickness, which is usually considered to be the low limit of ordinary Ni, Cr, cemented armour, the Charpy high nickel

* H. J. Jones, *Engineer*, vol. ciii., pp. 361-362. † *Engineer*, vol. xciii., p. 121.

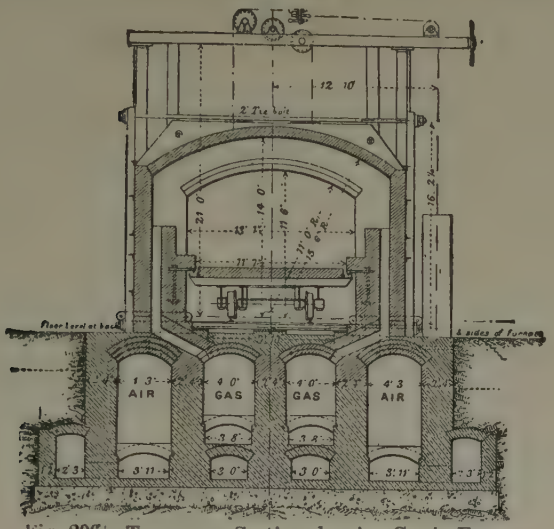


Fig. 206.—Transverse Section showing Car in Furnace.

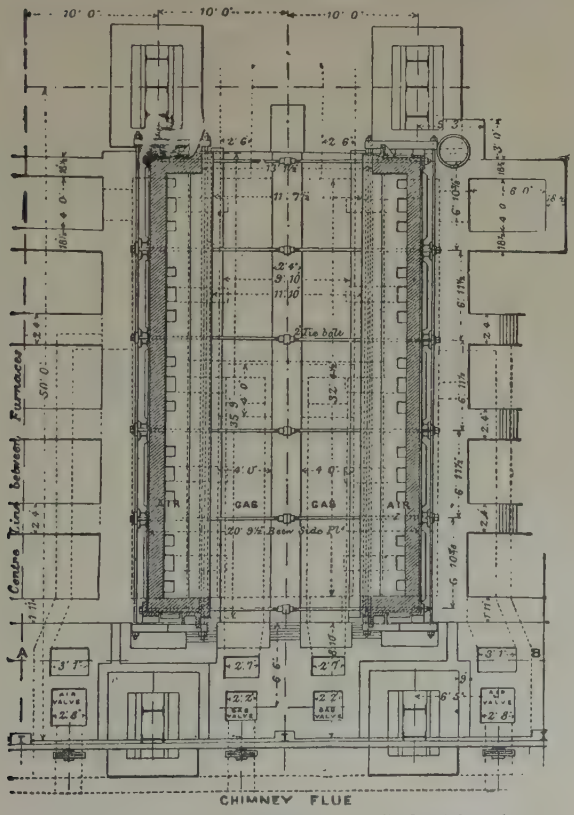


Fig. 207.—Plan of Gas Furnace for Carburising Armour Plates.

cemented plates appear to be the best as these may be made down to about 1 inch in thickness, and are thus of great value for destroyers, the shields of light guns, &c.*

Harveyised Plates.—The manufacture of armour plates by Harvey's process, at Messrs. Vickers' Works, Sheffield, is a good example of modern practice, and may be thus shortly described. Mild steel, made in open hearth furnaces, alloyed with varying percentages of Nickel, Chromium, &c., is cast into large ingot moulds, and when set, the ingots are taken to a reheating furnace and reheated for slabbing. When sufficiently heated—the largest ingots of 80 tons requiring 18 to 24 hours—the ingot is taken out and placed under a 8,000-ton hydraulic press, and slabbed to a definite thickness. Plates which are to be more than 12 inches thick pass direct from slabbing to the planing shop, where they are accurately machined to the required thickness; but if they are to be less than 12 inches thick they are, after slabbing, again heated, and rolled to the proper thickness. Forging under the press is now often dispensed with, the ingot being rolled direct.

The plate is then supported on knife edges some distance from the ground, to allow a free supply of air to pass round, and when cooled to a certain temperature is placed in a furnace and maintained at a low temperature, and then plunged into water. Pneumatic scaling hammers remove the scale, and the plate is then machined.

The next operation is the carburising, performed in a gas-fired furnace of the car type—*i.e.*, a furnace with movable hearth on wheels, 36 feet long and 21 feet wide (figs. 206, 207, 208, and 209). The outer walls of the furnace are of brickwork cased round with rolled steel plates, supported by rolled joists, and braced together by steel bolts. The car is built up of rolled H beams, the sides being of channel iron filled with sand. The top of the car is covered with several thicknesses of firebrick to protect it from the heat of the furnace, and upon them a series of flues is constructed extending the full length of the car, for the passage of the hot gases. Two plates, with a layer of a mixture of powdered animal and vegetable charcoal between them, are placed on the brickwork forming the flues, walls are built on all four sides, and the whole covered with sand. When the car is thus loaded it is run into the furnace, and the doors closed and made airtight. The hot gas enters at the back, the flames pass over the top, down the front, and through the flues under the plates to the chimney. The heat of the furnace is gradually increased, and kept at a suitable temperature for two or three weeks. The depth to which carburisation extends depends on the temperature of the furnace and length of time of treatment; it is also greatly facilitated by continuous firm compression of the carbonaceous material against the surfaces by the weight of the upper plate. After the carburising is finished, the plates are furnace-cooled for one week.

After carburising, and before hardening, all bending and machining is done; also any holes required are drilled and plugged with clay to prevent injury during hardening.

The hardening is the next important part of the process, and for this the plates are reheated to cherry redness, and are placed on an iron grid, and jets of water "squirted" on both top and bottom of the plate simultaneously. The pressure of water is about 10 lbs. per square inch—sufficient to prevent the formation of steam under the water, which would interfere with the chilling effect. The jets of water are delivered from a number of tubes, distributed over the whole of the upper and lower surfaces of the plate by

* Tressider, *Naval Annual*, 1905, pp. 366-371.

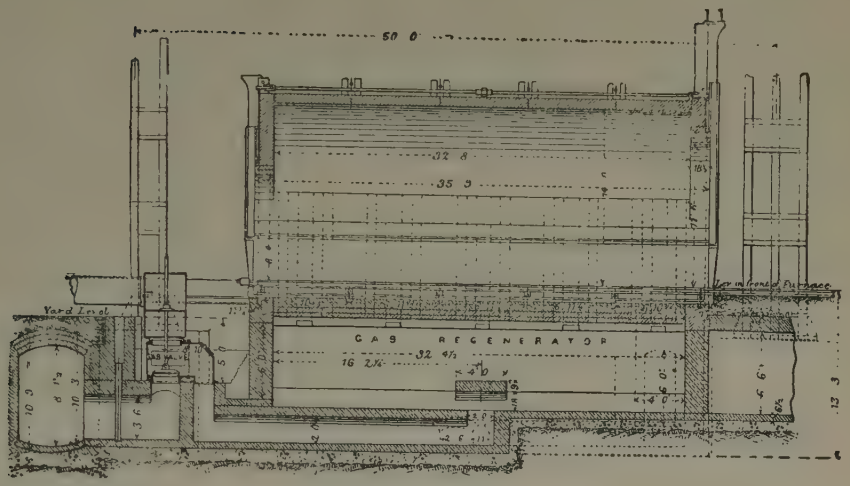


Fig. 208.—Longitudinal Section.

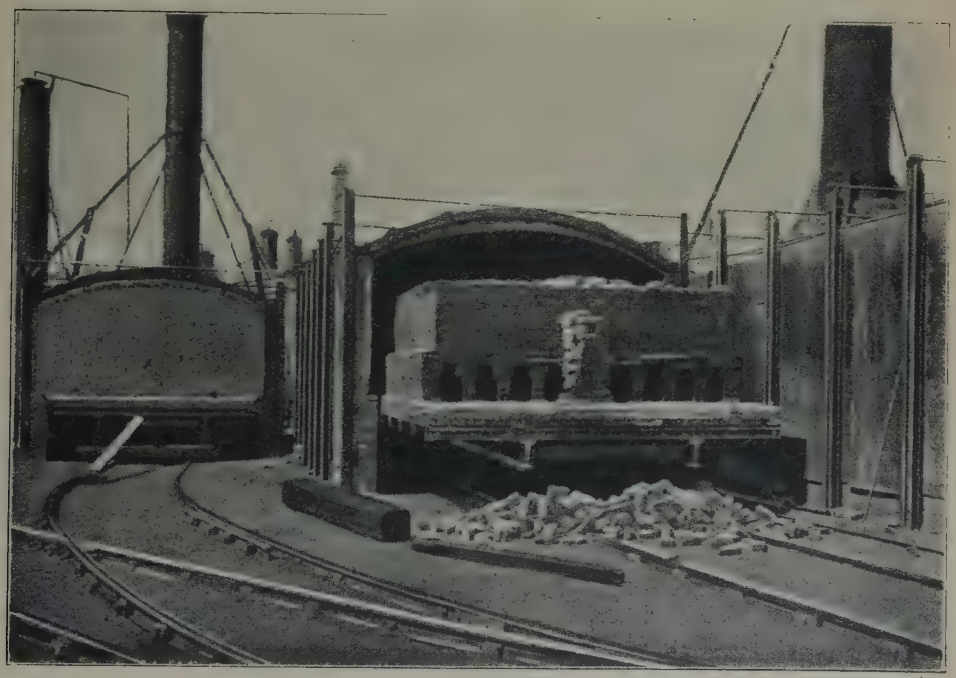


Fig. 209.—General view of Carburising Furnace for Armour Plates, showing Armour plates in position on car, built in with brickwork, with flues for circulation of the gases.

holes drilled in the tubes, ¼ inch in diameter, and 4 inches pitch. The upper system of tubes is supported on a movable carriage, so that they can be run out of the way when the plate is lifted on or off the gridiron. For a 14-inch plate the sprinkling takes three hours, and requires four to five thousand tons of water.* The depth affected by hardening is from 1 to 1½ inches. The hardening by means of jets of water is really Tressider's † process, in which the plates to be hardened are subjected to a douche or spray of cold water, which is supplied by a great number of small jets at sufficient pressure to prevent the retarding effect of an envelope of steam.

Any final adjustment that may be necessary after hardening can only be done by grinding, as it is not possible to machine the plates.

It was originally the custom to cover the backs of the plates, when in the cementing furnace, with Oxide of Iron instead of sand, to burn out or oxidise the Carbon, and thus insure a very soft steel at the back, but in practice sand has been found to give good results, and, so far as the author is able to obtain reliable information, seems to be generally employed.

Krupp Process.—Krupp's process consists essentially of carburising by means of gaseous hydrocarbons, followed by differential hardening. The furnace used for carburisation is of a special kind with movable hearth, and gas-fired. Two plates are placed upon supports on the hearth one above the other, with the faces to be carburised inwards, and separated so that the carburising gas may pass between them. The plates are completely walled round, except for the holes left to allow the furnace gases to pass over and under the outside of the plates, and the carburising gas to pass between. The hearth with the plates is then moved into the furnace, which is heated till the plates are at about the melting point of copper. At this stage the carburising gas—paraffin vapour, petroleum gas, illuminating gas, &c.—is passed between the plates. The inner surfaces of the plates thus become carburised, and the impoverished vapours pass into the furnace and burn there. As soon as the plates are sufficiently carburised the hearth is run out, and they are hardened in water by dipping or spraying, or they may be hardened in oil. It is usual to do all the necessary work on the plate before the final or differential heat treatment, in which the face is raised to a higher temperature than the back, so that on sudden cooling this side is rendered glass hard, and the back retains its toughness. How far this method is actually used in practice it is hard to say, as the details of the manufacture of armour plates at Krupp's works are not made public.

Cast Armour Plate.‡—The manufacture of cast armour is now in a highly efficient state. The metal is cast into moulds to produce a plate having ridges and channels. The hot casting is allowed to cool slowly in a special furnace, then removed to the cementing furnace, and upon the corrugated surface a carbonaceous composition is placed several inches in thickness, the furnace is raised to 900° to 1,100° C. for several days, then cooled slowly. The plate is again reheated and cooled four or five times with a gradual reduction of temperature each time, and at the final heating it is dipped into or sprayed with oil or water, so that the corrugated face, being rapidly cooled, will become hard, whilst the back remains soft and tough.

Materials Employed.—As regards the material now used for armour-plates, each manufacturer has a particular metal which he regards as best

* *Engineering*, vol. lxiv., 1897, p. 608. This supply is obtained, by special pumping machinery, from the Don, which runs past the works.

† Weaver, "Notes on Armour," *Journ. U.S. Artillery*, vol. iii., 1894, p. 417.

‡ H. J. Jones, *Engineer*, vol. ciii., p. 362; *ibid.*, vol. ci., p. 20.

for his purpose; but, generally, it is a special steel, with varying percentages of such metals as Nickel, Chromium, Manganese, Vanadium, and Tungsten. The hardness, toughness, and power of the plate to resist penetration depend very greatly upon the special heat treatment to which it is subjected, and there is no branch of metallurgy in which intelligent discriminating treatment has been more systematically applied, or has produced such remarkable results, as in armour-plate manufacture. Hadfield * states that the Nickel-Chrome Steel as forged may, by suitable heat treatment, have its tenacity increased from 40 to 90 per cent., and its ductility from 8 to 30 per cent.

The armour plates made for the United States Navy are said to contain about 3·25 per cent. of Nickel, and some analyses of an American armour plate made some years ago gave the following composition :—Carbon varied from 0·26 to 0·90 per cent.; Manganese, from 0·79 to 1·10 per cent.; and Nickel, from 2·39 to 2·50 per cent. A good average Krupp plate contains † Nickel, 3·5 per cent.; Chromium, 1·5 per cent.; Carbon, 0·3 per cent.; and Manganese, 0·7 per cent.

It is very important to remove both the bottom and the top of the ingot before forging down, and in practice nearly one-third of the ingot is removed from the top and about 5 per cent. from the bottom. According to Mr. S. E. Stuart,* it was the custom in America in 1893 not to use more than one-half the ingot, and, in any case, every precaution is taken to ensure that only the sound portions are forged down for the plates.

Wilson's Compound Armour Plates.—Although compound armour plates are now practically obsolete, some short indication of the methods of their manufacture may be of interest. By Wilson's process a soft tenacious wrought-iron plate is united with a hard steel plate in the ratio of $\frac{1}{3}$ steel to $\frac{2}{3}$ iron.

The iron plate, built up by welding together wrought-iron plates, is carefully manufactured to fit an iron mould of the shape of the compound plate required. The space between the iron plate and the inside of the mould is then filled with molten steel, which unites with the iron plate so well that the line of contact can hardly be seen. The compound body, when sufficiently cool, is removed from the mould and gradually re-heated in a furnace. The mass is then subjected to hydraulic pressure, after which it is rolled and reduced to the required thickness. The plate is next bent under the hydraulic press, and finally machined and drilled.

The Ellis process consists in combining a soft, tough iron back with a hard steel plate, by casting a layer of steel between the two.

Beardmore Process.—A process for making what may be called compound armour, and avoiding the tedious process of cementation, was patented four or five years ago, and is still being successfully worked by Messrs. Beardmore, of Glasgow. Ingots, consisting of layers of hard and soft steel perfectly united, are cast in the following manner :—

A layer of hard steel is run into a horizontal mould, the bottom of which is kept cool by a number of pipes through which cold air circulates. The bottom layer of the steel consequently sets very quickly, and while its upper part is still to some extent fluid, a second layer of softer metal is poured from the sides over the first, flows gently over it, and unites with it. Similarly, a third layer may be added, a considerable head of metal being allowed to give soundness. These ingots are pressed and rolled into plates, which can at once be bent to shape, machined, and chilled.

* Presidential Address, *Iron and Steel Inst. Journ.*, 1905.
† H. J. Jones, *Engineer*, vol. ciii., pp. 361-362.
‡ *Report of the Chief of Ordnance*, 1893, pp. 645-657.

By this means any desired depth of hard metal can be obtained on the face of the plate, while in the cementation process it is very difficult and costly to carburise to a greater depth than 2 inches, and the Beardmore process has the further great advantage that the time required to manufacture an armour plate is reduced to one-half.

This process is quite distinct from the old method of casting a layer of hard steel on to a wrought-iron plate, in which there was always some risk of the two metallic surfaces being somewhat imperfectly united, so that they were liable to part on receiving the impact of a shot. In the Beardmore process the union is so perfect—one metal passing imperceptibly into the other—that, on fracturing a plate, it is impossible to tell where the two metals join. Plates made by this process have recently been tested, and successfully resisted the attack of seven Krupp armour-piercing projectiles of $112\frac{1}{2}$ lbs. weight, with a striking energy equal to the British Admiralty requirements.

CHAPTER XIII

DIRECT PROCESSES OF STEEL MANUFACTURE.

NUMEROUS attempts have been made to produce wrought iron and dead soft steel direct from the ore, and it might at first sight appear that this was a more rational proceeding than to first make an impure cast iron, and subject this to a refining process to convert it into steel. Iron can be reduced in a very pure state from its ores at a comparatively low temperature, and even in the case of Phosphoric ores a metal can be obtained almost free from Phosphorus, the latter being removed as Phosphate of Iron at the low temperature employed, at the cost, however, of a considerable loss in iron.

Difficulties Involved.—The great difficulties, however, of reducing large quantities of ore by any of the known processes, coupled with the fact that the product is obtained as a spongy mass and not in a fluid state, have prevented any of the direct processes ever proving serious rivals to either the Bessemer or Siemens processes, the advantages that the latter possesses in the way of immense outputs, with resulting small labour costs per ton of material produced, being too great. Professor Howe, writing in 1892, expressed the opinion that the only future for direct processes was, as scrap producers, to prepare a metal for Siemens furnaces, or similar purposes, but events since then do not point to any serious development even in this direction.

The more probable development, in the author's opinion, lies in a combination between the direct and indirect processes on the lines proposed by Mr. Twynam (p. 203), by which the metal will be obtained as ingot iron or dead soft steel. The ordinary Siemens furnace is a direct process in so far that a small quantity of ore is reduced during the working of the charge, and if this could be increased to 50 per cent. of the charge without seriously decreasing the output of the furnaces, considerable economy would result, and further experiments on these lines will be watched with great interest. The processes, however, which we have to consider, known as "direct processes," are defined by Howe * as follows:—"Direct processes are those in which wrought iron or spongy iron is made direct from the ore, and either used as such or converted into steel usually by melting it with cast iron, more rarely by cementing it with carbonaceous material, or in which weld or even ingot steel is made direct from the ore."

These processes can only be used either in new countries, where small quantities of material are required, or where some other special conditions exist, such as very rich ores and fuel unsuitable mechanically for blast furnace work, or when the latter is exceptionally dear.

The following are descriptions of the better known direct methods of reduction, starting with the more primitive processes:—

Native Forge or Bloomery Processes.—Iron by these primitive processes is still made in some parts of India, Burmah, and the East Indian Islands. The furnaces used are of two kinds—those worked with natural draught and those with artificial blast. Those worked with natural draught

* Howe, *Metallurgy of Steel*, p. 259.

are usually situated on the exposed side of a hill, and have a stack of about 10 feet high cut in a bank of sandy clay, the breadth of the stack being about 1¾ feet at top and 5½ to 6 feet at bottom, and depth 1¾ feet at top, 1 foot at bottom, and widening at about the middle to 2 feet. The front of the stack is formed by a solid wall 3 feet thick. An arch cut in the foot of the bank communicates with the rectangular aperture at the bottom of the stack of the full width of the latter and about a foot high. This aperture is filled up with soft clay, through which about twenty nozzles or twyers of burnt clay are inserted. The furnace is dried, and then a bed of charcoal at the bottom is ignited, and ore and charcoal charged alternately (total, 420 lbs. ore, 437 lbs. charcoal). The slag is tapped eight or nine hours after starting and every half-hour until flow ceases. The furnace is then allowed to cool, the clay stopper removed, and the reduced iron (90 to 120 lbs.) taken out and freed from slag and unconsumed charcoal by reheating.

The furnaces worked by a blast from bellows are manipulated in a way similar to those worked by natural draught. The furnaces are made of sandy clay, and have stacks, 3 to 5 feet high, and 18 to 20 inches diameter, slightly conical in shape, with an arch cut out at the bottom for the blast nozzle. The ore and fuel are fed into the furnace, from an inclined platform at the top of the furnace. The operation lasts four to six hours, and the slag is tapped at intervals. The ores treated are usually brown hematites, broken small, and previously calcined with charcoal or brushwood. The reduced metal (a ball of iron 20 to 40 lbs. in weight) is preferably taken from the furnace by a pair of tongs from the top. In Borneo the furnace used is built of yellow clay, tied round by hoops of bamboo. It is a little more than 3 feet in height, and 10 feet in external diameter, with walls about 2 feet thick ; it is square on the inside, narrowing towards the hearth, which is 2 feet long, and 1 foot 7 inches wide. "Each furnace has three twyers, an opening for running off the slags, and an external basin for their reception." "The blast is not obtained by bellows, but by a blowing-engine, consisting of a single-acting cylinder of wood, open at the top and closed at the bottom, the blast being conveyed to the twyers by means of bamboo tubes." The ore treated is clay-ironstone, which is first roasted in heaps with wood, and then broken into small pieces the size of nuts, and charged into the furnace, ten times the bulk of fuel being used.

The slag is tapped off every twenty minutes, and the lump of iron obtained weighs about 100 lbs. It contains much intermingled slag, which is removed by dividing the piece into ten pieces, and hammering. Both soft and steely iron can be made in these furnaces, by altering the proportions of charge and nature of fuel used.

Wootz or **Indian steel** is manufactured from iron made in the ordinary Hindoo furnace, in the following way :—Small crucibles of refractory clay are used, in each of which about a pound of metal is placed, with a certain proportion of finely-chopped wood (*Asclepias gigantea* or *Cassia auriculata*). The crucibles are then covered with one or two green leaves (*Convolvulus laurifolius*) and wetted clay, and placed in the sun to dry. When the plugs have hardened, twenty to twenty-four of the crucibles are built, in an arched form, on the bottom of a small blast furnace, blown by bellows, and strongly heated for two to three hours. The furnace is then allowed to cool, the crucibles taken out and broken, the steel having melted down to a rounded button at the bottom of each pot. Probably in order that it may be completely melted the steel is over carburised, and before drawing out into bars the buttons are heated for several hours in a charcoal fire, urged by bellows, to a temperature not much below their melting point, and turned over before the blast, so that the metal may be partially decarburised.

Puddled Steel.—Though the production of steel by puddling is not, strictly speaking, a direct process, it is, nevertheless, convenient to refer to it in this chapter.

There is no essential difference between the manufacture of puddled iron and puddled steel, except that the puddled iron is decarburised to a greater extent than is the case with the steel. Highly carburised manganiferous pig-iron is generally used, and gives the best results. The furnace is similar to that employed for the manufacture of ordinary puddled iron, but the hearth is smaller in proportion to the grate, in order that a very high temperature may be attained. The charge is generally about 3 cwts., and consists of one kind of pig only. It is introduced in small fragments of uniform size, and is spread evenly, so as to insure uniform fusion without much oxidation. The charge is rendered perfectly fluid and covered with molten slag, in order that the fining may go on slowly. It is very important that the slag should be very fluid, and this is the reason for selecting a manganiferous pig, so that the presence of Protoxide of Manganese in the slag may increase the fluidity, without increasing the oxidising effect. The slag must be less basic than that used in the puddling of iron, and the stirring period lasts longer. The balling should be performed in a neutral or non-oxidising atmosphere, and the shingling done at a comparatively low temperature. Puddled steel is no longer manufactured to any extent, although thirty years ago considerable quantities were made.

The Catalan Process.—This process is now practically obsolete, but is of historical importance, having been used for centuries, and having only recently gone out of use. A low hearth, with one inclined twyer, is used, and the charge of ore and charcoal added separately, the charcoal on the twyer side of the hearth, and the ore in lumps not more than 2-inch cube on the other. The Carbon Monoxide, from the combustion of the charcoal, has a freer passage through the pile of lump ore than through the thick body of charcoal, and thus passes out this way, and so reduces the ore. A gentle blast is used at first, but after about two hours the lump ore is gradually pushed downwards, and blast increased; the ore, as it becomes reduced, is pushed down to the hot region near the twyer. As the charcoal burns away, more charcoal, mixed with some fine moistened ore, is added. Most of this fine ore passes down the twyer unreduced, and together with other unreduced ore, of which there is always a certain quantity pushed down with the reduced lump ore, forms a slag with the gangue, the temperature of the twyer region being sufficiently high for this purpose. The slag, which is essentially a basic ferrous silicate, when highly ferruginous, tends to dephosphorise and decarburise. The reduced part of the charge becomes pasty in the twyer region, and welds readily into a bloom. When the whole of the charge is worked down the blast is stopped, the bloom taken out, and hammered. In this process, by keeping the conditions as reducing as possible, so that the metal is not decarburised during the operation, steely iron can be produced, but this depends largely on the skill of the workmen; in any case the steel produced is of very uneven degrees of carburisation.

The American Bloomery Process.—This is still used in some parts of Canada and the United States, but is only applicable where rich, fine ores, charcoal, and labour, are cheap. In this process fine ore and charcoal are charged together; otherwise, in general features, it resembles the Catalan process. The hearth is nearly square, the bottom is formed by a water cooled cast-iron plate, and is covered by a hood of brickwork, enclosing a series of three or more syphon pipes, in which the blast is heated by the waste gases.

Stückofen (The Old High Bloomery).—This was a shaft furnace, 10 to 16 feet high, round or rectangular in section, about 2 feet 6 inches wide at the top, 4 feet 2 inches midway, and 1 foot 6 inches at the bottom. The furnace had one twyer 1 foot 2 inches to 1 foot 8 inches above the bottom, and a drawing hole about 2 feet wide at bottom, which was closed except when removing the bloom. In these furnaces there was a great tendency to make cast instead of malleable iron, and to guard against this the carburising tendencies were purposely restrained—*e.g.*, by charging a large proportion of ore to charcoal.

Husgafvel's High Bloomery or Continuous Stückofen.—This furnace is 26 feet high, 5 feet wide at boshes, and 4 feet wide at the throat. It has double air-cooled wrought-iron walls, separated by a continuous spiral diaphragm plate, thus enabling the blast to be heated by travelling circuitously downwards between the two walls. The air-way thus formed is connected at two or three places with the cold-air main above and with the hot-air main and twyers below. The lower 5 feet (between the top of the hearth and the boshes) are lined with fire-brick, the remainder of the shell being unprotected, and a movable air-cooled cast-iron section is provided between shaft and hearth. The hearth is a movable cast-iron box mounted on wheels and standing on a lifting platform. It has four water-cooled twyer-holes on each of two opposite sides and at two different levels, into which the blast nozzles can be adjusted by telescopic pipes and goose-necks; also four slag notches at different levels, trunnions for dumping, and a false bottom to save the hearth proper from accretions. Ores (chiefly Phosphoric bog-ores) and hammer scale are smelted in these furnaces with charcoal, both coarse and fine, in the following manner:—Charcoal and ore are charged in uniform horizontal layers, fine charcoal being added to fill up the interstices in the lump charcoal, and so prevent the fine ore sifting down too quickly. A fresh hearth is fitted into place, the twyers inserted in the lower twyer-holes, and the blast turned on. The burden descends gradually, and reaches the hearth quite reduced, and probably considerably carburised. The slag is tapped at intervals, but its level is kept slightly above that of the gradually-forming bloom, so that being highly ferruginous it assists the decarburising action of the blast. When the bloom has almost reached the level of the lower twyer-holes, the twyers are removed, the holes plugged, and the twyers raised to upper holes. When the bloom has reached the upper twyer-holes the blast is stopped, the hearth is lowered and immediately replaced by a fresh one, so that the furnace works continuously. With slow driving and light burden the slag becomes less ferruginous, less Phosphorus is eliminated, and the product becomes steely, or even cast iron. The composition of the slag varies greatly—with very slightly carburised blooms it contains 52·46 per cent. **FeO** (40·8 per cent. metallic iron), and with highly carburised blooms about 9·91 per cent. **FeO** (7·15 per cent. metallic iron).

Chenot's Process consisted in reducing iron ore in retorts either by *direct* heating with charcoal or *indirectly* by hot Carbon Monoxide from a gas producer. The furnace consisted of one or two vertical rectangular retorts, 28 to 33 feet high, 1 foot 4 inches to 1 foot 8 inches wide, and 4 feet 9 inches to 6 feet 6 inches long, heated by means of external fires. Below each retort was a sheet-iron water-cooled "refroidissoir," or cooler, in which the sponge was allowed to cool out of contact with the air. The charge of a furnace was about 1½ tons of calcined iron ore and about ½ ton of charcoal. The charge remained three days in the retort and three days in the cooler, a part of the sponge being withdrawn each day from the bottom of the cooler. The sponge was worked into blooms in a charcoal hearth or melted

in crucibles. The above applies to the *direct* process; in the *indirect* process the retorts were connected with gas producers and an upward current of gas maintained through the charge in the retorts.

Blair's Process, a modification of Chenot's process, was introduced in 1870. In this process it was attempted to overcome the difficulty of heating a large body of ore in the retorts, with consequent waste of fuel, by passing very hot producer gas through the ore and charcoal in the retorts, but this process has not been a commercial success.

Eames Process (Carbon Iron Company's Process).—In this process iron ore is reduced by mixing it with "retarded" (or "protected") coke or graphitic anthracite, and heating it by natural gas on the bed of a reverberatory furnace, which is covered with a layer of anthracite about 4 feet to 6 feet thick; the furnace is about 19 feet long, 6 feet broad, and 18 inches from roof to hearth, and is heated with natural gas at both ends, the products of combustion escaping through a flue in the middle of the roof. The charge consists of 1 ton dry rich ore (containing 62 to 65 per cent. iron) and about 5 cwts. of graphitic anthracite or retarded coke, all ground to pass a 16-mesh screen, mixed with water to render it plastic, and spread over the hearth in a layer about 4 inches thick. The metal is reduced at a low heat, and as reduced is protected from re-oxidation by the retarded coke with which it is mixed. If the metal is required for the open hearth furnace it is balled after about an hour and a-half, but if for rolling, balling takes longer, and the temperature must be raised to welding heat.

This process is said to have been worked successfully by the Carbon Iron Company, Pittsburg, U.S.A., where cheap fuel is obtainable. The spongy iron was partly taken direct to, and used in, the open hearth furnace (50 per cent. cast iron, 10 per cent. scrap, and 40 per cent. sponge-balls), and partly rolled into bars for use in crucible and open hearth processes.

Siemens Process, introduced in 1873, consisted in the reduction of fine ore by mixing it with coal and heating in a rotating furnace. The furnace was gas-fired and regenerative. The lining was of brick or bauxite, and fettled about 6 inches deep with hammer or roll scale or mill cinder, and then soft lumps of hematite or rich cinder were thrown in to roughen the surface and divide the charge while rotating. The rotator was charged at one end through a door, and the entrance for gas and air and exits for the products of combustion were at the other end. The charge consisted of pea-sized ore, bituminous coal for reduction, and limestone to form a moderately basic slag, and varied, according to size of furnace, from 24 to 50 cwts. For the first $2\frac{1}{2}$ hours the temperature was comparatively low and rotation slow—12 to 15 revolutions per minute. The charge then began to clot, slag formed, the temperature and rate of rotation were increased, and the slag tapped from time to time. Finally the temperature was raised to a white heat, and except for stoppages for balling and withdrawal the rate of rotation further increased. The whole operation lasted $4\frac{1}{2}$ to 6 hours. The fuel consumption was high and the loss heavy, while the iron was unsuitable for use as wrought iron, owing to its spongy nature and difficulty of separating it from entangled slag, but was suitable for use in the open hearth furnace.

SECTION II.

FINISHED STEEL.

CHAPTER XIV.

MECHANICAL TESTING OF MATERIALS.

THE great developments in all branches of engineering during recent years and the consequent demand for material of the highest quality necessitate the most exhaustive testing by all manufacturers of the steel made at their works, if they desire to maintain a reputation for producing a thoroughly reliable material. All steel used for structural and general engineering purposes should be subject to such tests, before leaving the works, that it may be reasonably certain that there will be no risk of failure after it has once left the manufacturer's hands. The special tests which it is advisable to make will largely depend upon the purpose for which the material is required, and in most cases the engineers specify their requirements in these respects, quite apart from such tests as the manufacturer may choose to make for his own satisfaction. It must be remembered that the object of testing materials under the conditions which we are considering is not to arrive at any *absolute* results, but simply to see if the material is good of its kind and suitable for the particular purpose for which it is required. It is sufficient, therefore, to compare it with some more or less arbitrary standard which has been selected, and which varies with different individual opinions and with varying classes of material. Thus, some engineers, having found as the result of experience that steel with 45 to 50 tons breaking-load gives the best results for tires, specify that their tire steels shall have a tensile strength within these limits, while others again specify from 48 to 52 tons.

Broadly speaking, the tests applied may be divided into two classes:—(1) Hot tests to insure that the metal is free from all red shortness at all temperatures above a red heat, and is of good welding qualities; and (2) cold tests to insure that the metal possesses the required strength, elasticity, ductility, &c., and is free from cold shortness or tendency to brittleness when cold.

The ordinary welding and hot plating tests have already been, to some extent, referred to under the Bessemer and Siemens processes, and these are described more fully at the end of this chapter. What we have more especially to consider now are the systematic methods for investigating the properties of steel by the application of stress and the deductions to be drawn from the results obtained.

The stress may be applied gradually in the form of a direct pull, or may be applied gradually as a direct thrust, to test the resistance of the material to crushing. Torsional or twisting stresses and shearing stresses may also be applied, and each of the several methods adopted furnishes different information as to the qualities of the material under trial. Instead of

applying the load gradually, it may be applied suddenly by means of a falling weight or the blow of a hammer to test the resistance of the material to deformation or fracture by sudden shock.

In the case of a gradually-applied load, the most usual test for steel is to determine the maximum stress or tensile strength, as, incidentally, in carrying out this test a considerable amount of other information as to the general properties of the material is obtained. Before describing in detail the methods and machines used for testing, it will be advisable to define certain terms which are used to express the results obtained in ordinary testing machines—viz., tensile strength, elastic limit, elongation, reduction of area, and yield-point.

The Tensile Strength — *Ultimate or Maximum Stress; Maximum Load*—may be defined as the maximum stress which a bar of the material can sustain without rupture when a pulling force is applied gradually in the direction of its length. It is expressed in tons, pounds, or kilogrammes per unit area of the cross-section of the test bar, usually per square inch or per square millimetre.

Elastic Limit is the maximum stress a material can bear without suffering permanent distortion or set. This is likewise expressed in tons, pounds, or kilogrammes per unit area of cross-section, usually per square inch or per square millimetre. Within certain limits steel is an elastic body, and, on being elongated by a tensile stress, returns to its original dimensions when the force ceases to be applied.

When the applied force exceeds a certain amount, the material becomes permanently distorted, and *permanent set* takes place. Within the limits of elasticity, under equal variation of loading, a metal bar of uniform section lengthens or shortens equally through its entire length, and on removal of the load returns to its original size; and such loading may be repeated indefinitely, subject to the condition known as fatigue, without deterioration of the material in any way. If, however, the material is once subjected to stresses in excess of its elastic limit, it is permanently altered, and under a series of such stresses it becomes more or less plastic and finally breaks down. Professor Unwin * distinguished the two deformations referred to as "elastic deformation," that which disappears when the load is removed, and "plastic deformation," that permanent distortion which remains after the load is removed, and these probably give as correct an idea of the physical state of the material when subjected to the two stresses as it is possible to convey; the elastic limit seems to mark the boundary between the elastic and plastic conditions.

Modulus of Elasticity (Young's Modulus).—As a perfectly elastic body shortens or lengthens equally under equal additions of stress, it is therefore obvious there must be some force which would stretch such a body to twice its length, and this stress expressed in tons, pounds, or kilogrammes per unit area of cross-section is termed the modulus of elasticity. Thus, assuming a steel bar 3 inches long and 1 square inch in sectional area is stretched, by a force of 13 tons, ·003 of an inch without permanent set, by a simple proportion sum we are able to find the force which will be required to stretch it 3 inches. Thus—

Extension.	Inches.		Tons.	Tons.
·003	: 3	::	13	: x

$$\therefore \quad x = \frac{39}{\cdot 003} = 13{,}000 \text{ tons per sq. in.},$$

and this is known as Young's modulus.

* "Testing of Materials of Construction," p. 18.

Young's modulus may be defined as the force which, acting in the direction of the length of a bar, when applied to one end of it, the other end being fixed, would double the length of the bar, the cross-section being of the unit area (say 1 square inch). As no metallic substance can thus be doubled in length, the modulus may be defined as 1,000 times the force, which would increase the length by the $\frac{1}{1000}$ part of the whole, or 1,000,000 times the force, which would increase the length by the $\frac{1}{1000000}$ part of the whole.

In wrought iron and mild steel the value of Young's modulus is about 13,000 tons per square inch; in other words, a stress of 1 ton per square inch produces an extension which is $\frac{1}{13000}$ of the original length of the bar.

Young's modulus can be calculated by the following formula:—

$$\frac{p \times L}{\omega \times l} = E,$$

where p = stress, L = original length of sample,
ω = original sectional area, l = extension measured.

Elongation.—This is the increase in length which a metal bar undergoes when subjected to a gradually applied tensile stress, in the direction of its length, sufficient to cause fracture. It is usually expressed as the percentage increase on the original length of the bar. This elongation of the bar takes place equally throughout its entire length so long as the load is maintained well within the elastic limit, but as soon as this is much exceeded the bar elongates somewhat unequally in different parts, and the ultimate elongation expressed in percentages is simply the sum of these variable local elongations. It is of the greatest importance when referring to elongation to state always the *length of the sample* on which the experiment has been made, as owing to a great local extension always taking place at the point of fracture, unless this is done the results are most misleading. Thus, a good *local* extension on a length of 3 inches would make the ultimate percentage of elongation appear very much higher than if the results were obtained on an 8 or 10-inch sample.

Reduction of Area.—This is the amount of contraction of area which takes place at the point of fracture when a metal bar is broken by a direct pulling force. It is usually expressed in percentages of contraction of area as compared with the original sectional area of the bar. Both the elongation and reduction of area furnish valuable indications of the ductility of the material under examination, and the greater they are for the same class of material—*i.e.*, for material having approximately the same tensile strength and elastic limit—the softer and more ductile the material may as a rule be considered.

Yield Point.—This is a very noticeable point in rolled or hammered iron or steel, which occurs just when the elastic limit has been exceeded, and which apparently marks the breaking down of the original molecular arrangement. At this point, without any increase of stress, the bar suddenly and permanently elongates by a considerable amount, often equal to 100 times its whole previous elongation, and then again recovers somewhat its original rigidity, and a greater load has to be applied before there is any further elongation or the bar can be fractured.

In ordinary commercial testing this point is generally taken as the elastic limit, and is very noticeable by the "drop of the beam" of the

testing machine; but this is incorrect, as it is not identical with the elastic limit, although very near it.

In investigating the properties of a material and its suitability for structural work or other engineering purposes, in which it will be subjected to varied stresses, probably nothing is of greater importance than the elastic limit and the yield point, as however great the ultimate breaking load may be, when once this elastic limit is passed we are dealing with a plastic material which, under the action of stress, will continue to go on deforming, and consequently must be an unsafe material to use. In actual practice, however, this determination is often omitted by steel makers, and is frequently not specified by engineers, the ultimate breaking load, elongation, and contraction of area being considered sufficient.

Stress Diagrams.—A stress-strain diagram with vernier readings will probably make clearer what takes place during the testing of an ordinary steel bar. Fig. 210 is from an automatic record diagram taken by the machine at Cooper's Hill. On the horizontal line are set out the percentage extensions or elongations of the bar, and on the vertical line the stress in tons. The extensions on the original diagram before reduction, were shown as 3·025 times the actual extension, but for convenience are divided into percentages of elongation on the original length of the bar. As the stress gradually increases the bar slightly elongates along its entire length, but very slightly, until it registers a load of 13·5 tons. This point marks the elastic limit, and it will be noticed that the elongation up to this point has been almost inappreciable and quite uniform for every equal increment of the load, an extension of about ·0011 of an inch taking place for each increase of 1 ton. At a load of 13·5 tons this regularity vanishes, and between 13·5 and 14 tons there is a very noticeable and sudden increase in the extension of the bar, and at the point D this is equal to ·038 of an inch, or nearly 33 times that produced by any previous increment of 1 ton in the load.

ORDINARY OR COMMERCIAL TESTS MADE ON BAR OF OPEN HEARTH MILD STEEL.—READINGS TAKEN FROM SCALE ON THE TESTING MACHINE.

Original Dimensions.	Dimensions after Testing.	Percentages of Extension, &c.
Length, 10 inches, . . .	12·658	26·58 per cent. extension.
Sectional area, ·6320, . .	·2678	57·62 per cent. contraction of area.

Elastic limit, 13·5 tons, equal to 21·36 tons per square inch; maximum stress, 19·86 tons, equal to 31·42 tons per square inch.

OPEN HEARTH MILD STEEL—RESULTS OBTAINED FROM A SERIES OF VERNIER READINGS.

Loads in Tons.	Vernier Readings.	Vernier Extensions. 3·025 actual.	Total Extension. 3·025 actual.	
1	1·7534	...	...	
2	1·7566	·0032	·0032	
3	1·7599	·0033	·0065	
4	1·7632	·0033	·0098	
5	1·7665	·0033	·0131	Modulus of elasticity.
6	1·7699	·0034	·0165	
7	1·7732	·0033	·0198	$E = \frac{12 \times 10}{\cdot 632 \times \cdot 0396} \times 3 \cdot 025 = 14{,}504$ tons per sq. in.
8	1·7765	·0033	·0231	
9	1·7797	·0032	·0263	
10	1·7830	·0033	·0296	
11	1·7863	·0033	·0329	
12	1·7896	·0033	·0362	
13	1·7930	·0034	·0396	Elastic limit.
14	1·9076	·1146	...	Yield point.

N.B.—The vernier readings are 3·025 times the actual extension.

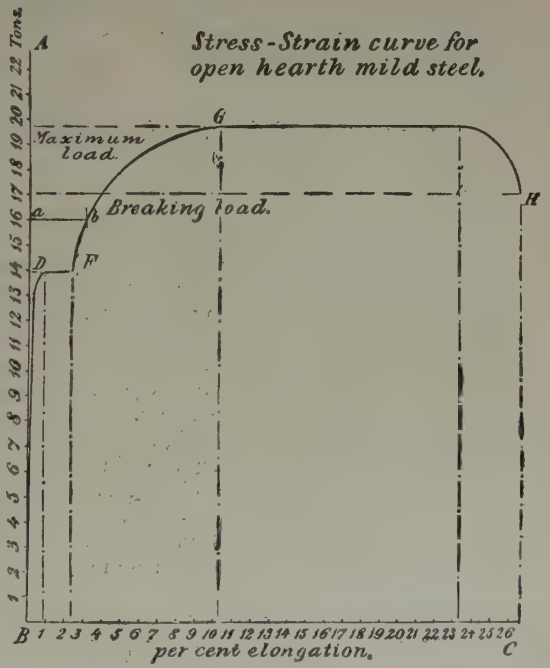


Fig. 210.—Elastic limit, 13·5 tons; D, yield point; F to G, curve of extension between yield point and maximum load; G, maximum load, 19·86 tons; H, breaking load, 17 tons. By dropping perpendiculars from any point in the curve, as at D, F, G, or H, to cut the base line, we get the percentage elongation for any particular load. Thus, at D it is rather under 1 per cent., at F just under 2·5 per cent., at G 10·25 per cent., and at H 26·65 per cent. Similarly, by drawing lines from any point in the curve parallel to the base line to cut the perpendicular load line, we can get the load on the specimen for any particular point in the curve.

At this point suddenly, without any increase in the load, there is a further most marked increase in the elongation from D to F, equal to 60 or 70 times the uniform elongation which has previously taken place; this marks the yield point. At the point F this elongation suddenly stops until a further load is applied, when the specimen gradually elongates as the stress increases up to the point G, which marks the maximum load the sample will bear. From this point the specimen still goes on elongating notwith-

standing the decreasing load, and finally breaks at H. This diagram shows that the maximum tensile stress and the actual breaking load are very different things, the latter being considerably less (viz., 17 tons against 19·86 tons) owing to the fracture taking place on a much reduced sectional area due to the "necking" of the specimen at the point of local contraction. From G to H gives the history of the specimen from the time the maximum load is applied until local contraction takes place and it is drawn out and finally ruptured. By plotting out the actual loads and extensions as shown, the amount of extension for any given load can be obtained. Thus, suppose we want the elongation, say, at 16 tons, we draw a horizontal line at *a* to intersect the curve at *b*, when the extension will be given by the length of *a b*. By the same means we can find the extension for any given load. Although the above curve was taken with a recorder, curves can thus be plotted, for any given specimen, by taking a number of readings and by placing the loads along the vertical and some multiple of the actual elongation along the horizontal, and joining up the points obtained. The elongation can be expressed in actual or percentage elongations.

Testing Machines.

The simplest mode of testing materials is to suspend a dead load from the specimen, but, except for very small sections, it is impossible to handle the large weights necessary. To overcome this difficulty a smaller weight with a lever interposed can be employed, and the earliest forms of testing machines were constructed in this way. A difficulty arises, however, as the lever becomes inclined when the bar stretches, and it is then necessary to arrange to take up the elongation of the sample by a screw or hydraulic press and ram, or some similar device, to keep the lever horizontal, and some arrangement of this kind is now always adopted.

Machines may be either horizontal or vertical, and each has its own advantages according to the special work required. For ordinary work the vertical type is probably the more useful. The modern lever machine may be regarded as a weighing machine, in which the ram to which the specimen is fixed, and which produces the pull, represents the body to be weighed on the platform, and tends to pull the lever carrying the weights up against the top stop until these are sufficient to balance the pull, which it then measures and registers.

One mode of applying the weight is to use a scale pan and place separate weights in it, and this is in actual use in some machines; but the more usual plan, instead of varying the weights, is to keep the weight constant and vary the leverage by means of a jockey or travelling weight, which rolls upon the lever beam, and can thus be readily moved to or from the fulcrum of the lever. Another form of machine which is in use in France, is the Maillard machine, in which the lever-weighing apparatus is entirely dispensed with, the pull on the specimen being exerted by a hydraulic ram, and transmitted through a bent crosshead holding the specimen, to another chamber containing an incompressible fluid, the pressure on which is registered by an ordinary pressure gauge, or by a column of Mercury.

In England the Wicksteed machine, and for a cheaper form the Adamson, may be taken as fairly representative types of the single and multiple lever machines in use in modern steel works, and therefore a sketch and short description of these two types are given to enable the student to grasp the essential details of these machines which he may have to use.

Fig. 211 is a diagram prepared by Mr. Hopps, superintendent of the workshops at Cooper's Hill for illustrating the *principle* of the Wicksteed machine. U and S are two crossheads connected by strong screws, T T, to the hydraulic ram. The test piece is held at one end by grips in the top crosshead, U, the other end being gripped by the end of the shackle supported on a knife-edge on the main lever. Water, from the pump or accumulator, is forced into the cylinder through the pipe shown, and the ram in the cylinder tends to move down in the direction indicated by the arrow, and this downward pull is then counterbalanced by advancing a movable weight along the main lever which exerts a pulling force on the specimen in an upward direction. The main lever or beam is graduated in tons and tenths of tons, and at any particular moment therefore the pull on the sample under stress can be obtained. As the stress is gradually increased the balance weight on the lever is advanced to keep the latter floating in a horizontal position until the elastic limit, maximum stress, or breaking load, as the case may be, is determined. This is the principle of all single lever machines.

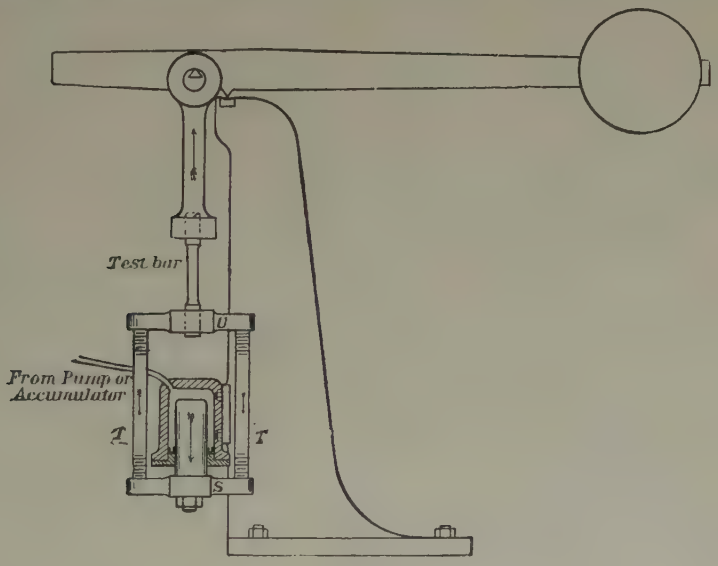


Fig. 211.

Wicksteed Testing Machine.—This testing machine (fig. 212) consists essentially of a beam resting, by means of a knife-edge, on a standard of cast-iron. In connection with the beam is a screwed bar, O, running the whole length of the beam, and by rotating this bar motion is imparted to a weight of exactly 30 cwts., which moves by means of four rollers along the beam. This beam is about 21 feet in length, and is supported by a knife-edge of hardened steel.

The bar to be tested is attached to the shackles of cast steel, which latter rest on a similar knife-edge to the one for the beam. Thus, by moving the weight of 30 cwts. towards the longer end of the beam, any required weight or stress can be placed on the specimen up to 100 tons.

In fig. 212 is shown a general view of the latest form of Wicksteed testing machine, built a few years ago for the Bradford Technical College by

Messrs. Buckton, and described by Mr. G. F. Charnock, head of the engineering department. Both the drawing and description are taken from *Engineering* with some details supplied by Messrs. Buckton.

The Wicksteed machine is often worked from a screw pump or compressor, but there are several distinct advantages secured by the employment of an accumulator. This is shown at G, and the ram, H, having a diameter of 4½ inches, is loaded to a pressure of 3,000 lbs. per square inch, from a crosshead, I, fixed at its upper extremity from which is suspended by means of four rods a load of about 24 tons of cast-iron slabs, I^1, 18 inches by 9 inches by 2¾ inches, bonded together in courses round a square opening left in the centre for the cylinder, K. The whole is neatly cased in with a wooden frame filled in with boarding. The foundation for the accumulator consists of a stone 6 feet by 6 feet by 2 feet, weighing about 5¾ tons. The accumulator is supplied by an automatic belt-driven pump, L, supported upon a frame which also forms the tank from which the supply is drawn. The pump is arranged on the well-known differential principle, to give a

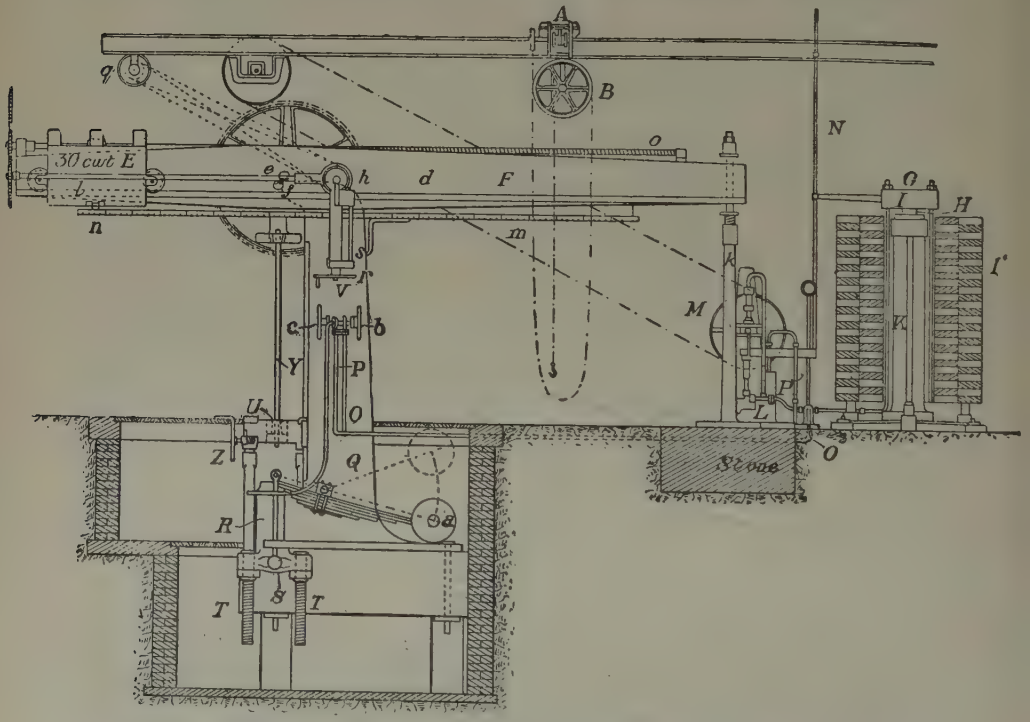


Fig. 212.—Wicksteed Testing Machine, Bradford College—A, Small overhead traveller; B, 2-ton pulley blocks; E, travelling poise-weight; F, main lever; G, accumulator; H, accumulator ram; I, crosshead to ram carrying weights; K, cylinder of accumulator; L, pump for supplying accumulator; O, pressure pipe from accumulator; P, exhaust pipe to accumulator; Q, main cast-iron standard; R, hydraulic straining cylinder; S and U, crossheads attached to hydraulic ram; T T, strong screws connecting crossheads, S and U; Z, worm gearing for operating screws, T; *a*, balance-weight; Y, specimen; *b*, pressure valve; *c*, exhaust valve; *e*, knife-edge fulcrum for F; *f*, knife-edge for shackles; *m*, graduated scale; *n*, vernier; *o*, screw for moving poise-weight; *q*, counter shaft; *r*, hand-wheel for slow movement of E; *s*, reversing handle.

continuous delivery during both strokes, although single-acting. In this case, however, there are two plungers, each working in its own barrel, one above and the other below the crank, from which motion is imparted by means of a slotted cross-slide. The lower plunger has twice the sectional area of the upper one, and there is only one suction and one delivery valve, both in connection with the bottom barrel. Therefore during the down-stroke, of the whole cylinder volume discharged through the delivery valve, half returns to fill the upper barrel by the pipe shown, and the other half goes direct to the accumulator, whereas during the up-stroke a whole volume is drawn through the suction valve, and the half volume in the upper barrel is delivered to the accumulator. The belt is thrown on to the loose pulley, M, by means of the tappet-rod, N, and lever, when the accumulator reaches the upper limit of its stroke. The whole arrangement has been found to work in a highly satisfactory manner, and gives no trouble whatever. The pressure and exhaust pipes, O, P, from the accumulator to the machine and return, are laid in a brick-lined trench formed in the floor, and covered in with 3-inch boards, so that the joints are easy of inspection.

The machine itself consists of the main standard, Q, a heavy box casting, firmly secured to a massive stone foundation contained in a brick-lined pit, covered in with a removable flooring of 3-inch hard wood boards. The latter can easily be lifted for testing long specimens, when the lower platform, accessible by steps, becomes the working floor. The hydraulic straining cylinder, R, of 10 inches diameter and 12 inches stroke, is securely fixed in an inverted position to the base of the standard. The ram thus acts downwards, its crosshead, S, being connected by the two strong side screws, T, to the upper crosshead, U, which is guided by V-slides on the face of the main standard, and in which is formed (1) the gripping-box for the lower end of a tension specimen, Y, as shown in fig. 212; (2) a face for the upper end of a compression specimen, W, as seen in figs. 213 and 214; or (3) a presser foot to apply the load at the centre of a beam specimen. The screws, T, are operated by worm gearing, worked by the handle, Z, and enable the adjustment to any length of either tension or compression specimen up to 6 feet to be effected. The balance-weight, *a*, carried upon the end of spring levers, causes the return stroke of the ram to be made after the conclusion of a test. The valve, *b*, admitting pressure from the accumulator, and the exhaust valve, *c*, for return to tank, are of the screw pattern worked by hand-wheels instead of levers, as usual, and are easily adjustable to suit any speed of testing desired.

The main lever or steelyard, F, is double-ended, one of the distinguishing features of this type of machine, and in the present instance is of cast iron, probably possessing greater rigidity than if built up of wrought-iron plates. It turns upon a knife-edged main fulcrum, *e*, on the top of the main standard, and from a second knife-edge, *f*, hangs the upper shackle, *g*, which carries the gripping-box for the upper end of a tension specimen (see fig. 212), or from it may be suspended by the four strong rods, *h*, the lower table, *i*, having a face for the bottom end of a compression specimen as in figs. 213 and 214. The knife-edges are of hardened steel, 20 inches long, or 1 inch for every 5 tons of load, and the fulcrum distance between them is 3 inches. The motion of the end of the lever is limited by stops, fitted with strong steel springs, on the post, *k*. The travelling poise-weight, E, of 30 cwts., is of rectangular form, overhanging the sides of the main lever so that its centre of gravity may be kept on the plane passing through the knife-edges. The graduated scale, *m*, is 200 inches long, reading 2 inches to the ton, and is carried upon brackets depending from the side of the lever, instead of being placed upon the lever itself

as in some previous machines. This is a great improvement, vastly increasing the legibility of the scale. The vernier, *n*, which easily reads to $\frac{1}{100}$ ton, is as usual carried by the poise-weight, and its position is adjustable, so that when the lever has been put in balance, it may be set to zero on the scale. A peculiarity should be noticed in connection with the lever of Mr. Wicksteed's machine. If this were balanced by a counterweight in the ordinary manner, the poise would indicate zero when

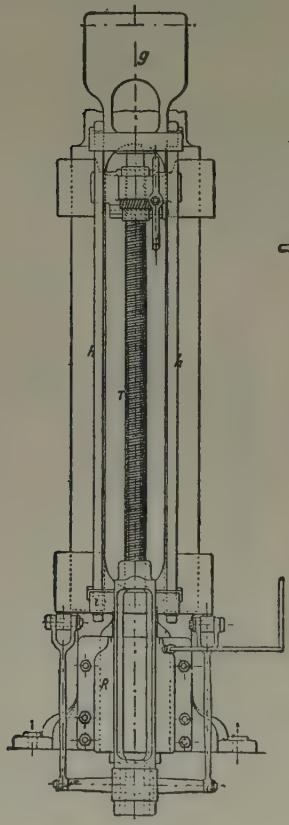


Fig. 213.

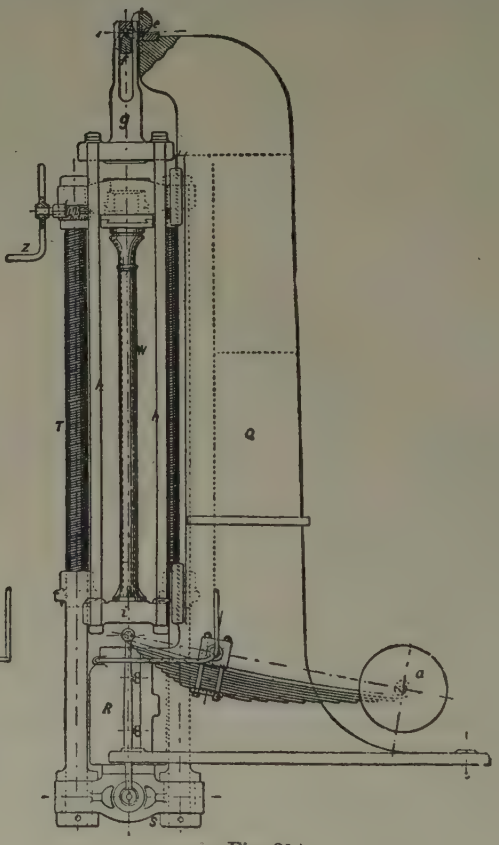


Fig. 214.

Arrangement for making Compression Tests on long Cast-iron or other Bars or Columns—*g*, Shackle; *h*, rods carrying compression table, *i*; *i*, compression table.

on the fulcrum, and as the long arm would be of the same length as the scale, the leverage ratio would be

$$\frac{200 \text{ inches length of scale}}{3 \text{ inches fulcrum distance}} = 66{\cdot}6 \text{ to } 1.$$

The steelyard is, however, double-ended, and the poise must be travelled back over the short arm until the lever is in equilibrium, and at this point the zero of the scale must be taken. Hence the poise when at zero on the negative end of the lever is balancing weight of equal moment on the

positive end, and as it travels towards the fulcrum, the effect is to deliver back again to the long arm the weight previously balanced. Therefore the actual weight used for measuring the stress is really double the weight of the poise—viz., 3 tons—or the virtual long arm is half the length of the scale, giving a leverage ratio of only 33·3 to 1. This great weight and low velocity ratio is highly favourable to rapid and accurate testing, because it minimises the unrecorded effects of inertia due to vertical oscillations of the lever, and at the same time gives the advantage of a large scale reading, and a comparatively light travelling poise.

The poise-weight is mounted on four rollers, which run on rails cast on the sides of the lever, and it is moved by a quick-threaded screw, *o*, which is rotated by spur-wheels from a shaft fitted with Hooke's joint to allow of the motion of the lever, in connection with reversing gear, *p*, driven by open and crossed belts from the countershaft, *q*. A hand-wheel, *r*, is also provided for very slow motion or fine adjustment, and this, together with the reversing handle, *s*, and hydraulic valves, *b* and *c*, is placed within easy reach of the operator, who, without moving from his place, has the specimen in full sight, and can easily observe the movement of the lever.

A is a small overhead traveller actuated by hand-chains fitted with a 2-ton pulley block, B, for moving large specimens and for lifting different parts of the machine.

The arrangement for making compression tests, shown in figs. 213 and 214, is capable of dealing with specimens up to 6 feet high and 9 by 9 inches in cross-section, and the convenience of a vertical machine probably ends when lengths greater than this or about the height of a man have to be tested.

Adamson Machine.—This is a multiple lever testing machine, and a skeleton sketch of the system of levers is shown in fig. 215. The first right-hand lever, A′, is made of 10 powers, so that the force on the lever is $\frac{1}{10}$ of that on the specimen, and, in passing to the end of the second 10-power lever, B′, the load becomes $\frac{1}{100}$ of that on the specimen; it then passes forward to C′, which is 12 powers, at the end of which the load is reduced to $\frac{1}{1200}$ of the force on the specimen, passing finally from the third lever to the end of the fourth, D, of 12 powers, where the force is $\frac{1}{14400}$ of that on the sample, and where the scale plate is fixed for receiving the 3-lb. weights.

Referring to fig. 215, the specimen, L, is held in the crossheads, H and K, by wedges which fit into grip-boxes having cylindrical bushes, as shown in separate sketch (fig. 217). The load is put upon the specimen by means of a hydraulic ram, D, working in the cast-steel cylinder, C, actuated by a pair of small ram pumps, E, worked with double crank-shaft, F, driven either by hand or other power, with a friction clutch to stop or start as required. The centres of motion of the pumps are directly opposite each other, so that one pump is constantly forcing whilst the other draws water or other fluid from the cistern, G, under the hydraulic ram cylinder. This gives a steady outward action on the ram, while the force is transmitted to the crosshead or grip-box, H, holding one end of the specimen under test, through two steel side bolts, I, with adjustable screw ends, so as to regulate the distance between the two sets of cross-head grip-boxes, in order to suit the varying lengths of test pieces and to transmit the stress in a direct horizontal line. The opposite end of the test piece, L. is held in similar manner in crosshead, K, attached to the main lever system, and the entire force is passed through the lever pins resting on hardened knife-edges. The registered lever is divided into

main divisions, which show an increased stress of 1,000 lbs. on the specimen, and these divisions are subdivided to show an increase or decrease of 20

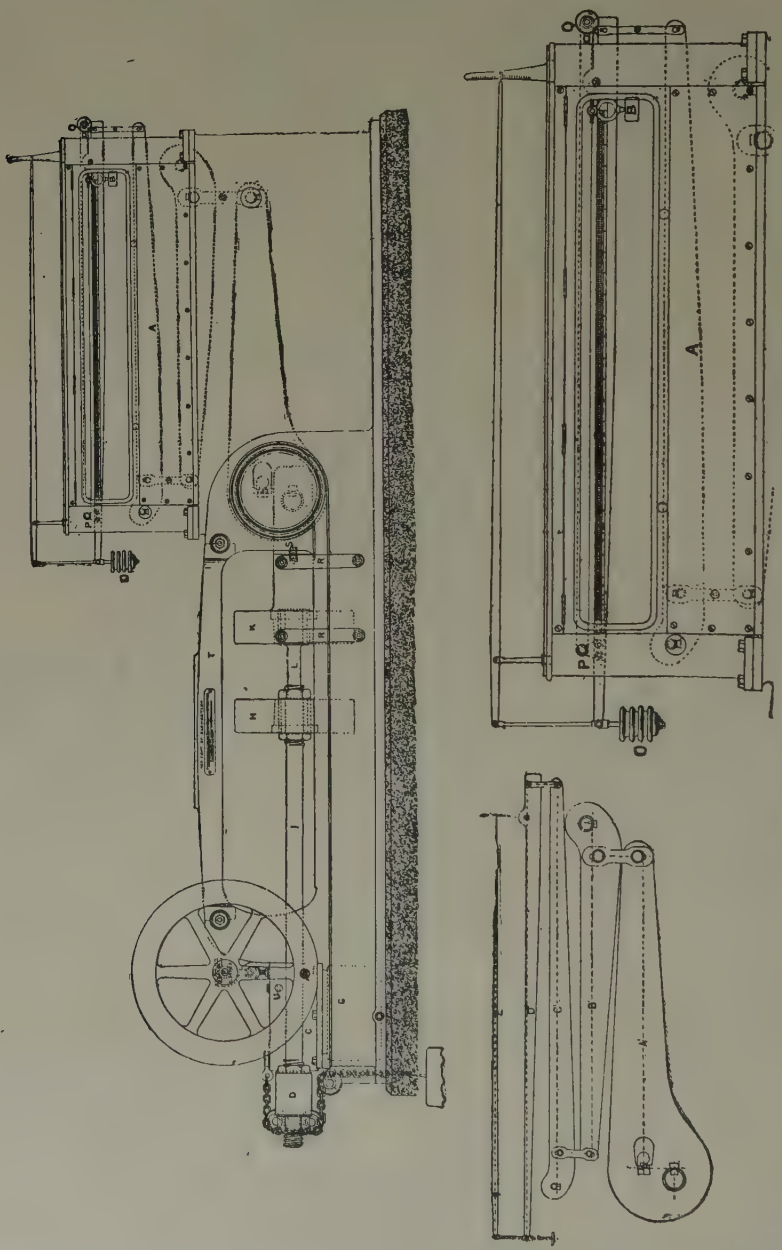


Fig. 215.—Adamson Lever Testing Machine.

lbs., so that great refinement is obtained by the movement of a very light jockey-weight along the beam. The total weights required to register

230,000 lbs. are four 3-lb. weights, used at the end of the 14,400-power lever, and one floating weight of 4 lbs., the aggregate of the weights being only 16 lbs.

The jockey or floating weight, B, is moved along the lever beam by a light cord having a pulley, P, fixed on the outer end of the lever, and another pulley, Q, against the outer end of the lever box. By turning the latter pulley by a hand-wheel, the weight is moved to and fro to maintain the load on the test piece at any given moment of time.

In commencing to test, the jockey-weight is run back to zero and the pump put in motion, and, when the strain comes upon the specimen, the weight is advanced along the beam to keep it floating evenly between the stops and just balance the load on the specimen.

The hydraulic ram, when forced out by the pumps after the rupture of the specimen, is brought back into position by a weight suspended by a chain passing over two pulleys fixed on the head of the ram, one end of the chain being fixed to the upper portion of the cylinder. U is a hand screw for releasing the water from the cylinder, which passes back into the cistern below.

For ordinary work, this machine gives good results, is very rapid, and, if used with care, does not readily get out of order.

It is more especially adapted for tensile testing, but, with some modifications and an additional apparatus, can be used for compression tests and punching.

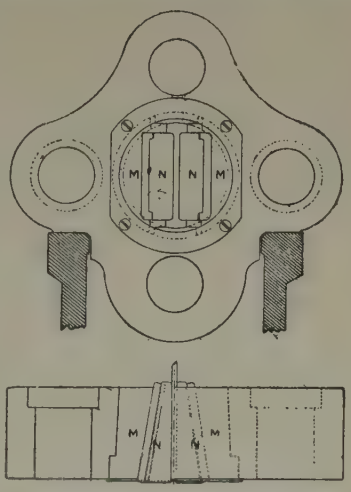


Fig. 216.— Gripping-box Showing Taper Wedges for Holding Specimen.

Calibrating Testing Machines.— In these days, when materials required for structural work are constantly being tested by engineers at machines away from the works as a check upon the works' results, the necessity of tests being reliable from a business point of view, apart from any consideration as to the great importance of obtaining accuracy in the absolute sense, is too obvious to need emphasising. Testing, like other machines, even assuming they are quite accurate at first, are liable to get out of order, which renders their verification an important matter.

The calibration of a testing machine is perhaps one of the most useful lessons a student can have, and, if done carefully, will give him an intelligent grasp of the principle and details of the machine he has to use, which he can hardly gain in any other way.

Professor Unwin * considers the three essential points to test are :—

(1) If the jockey-weight is of the weight indicated.

(2) To determine the leverage of the machine—that is, to see if the fulcrum distance agrees with the unit length taken on the scale.

(3) To determine what error, if any, is introduced by the centres of gravity of the jockey-weight and of the lever not coinciding with a line drawn through their knife edges.

In testing the weight in a type of machine like the Wicksteed, the

* Cantor Lecture, March 28, 1887, p. 15.

first thing to be done is to travel the jockey-weight back a little behind the fixed knife edge until the lever is exactly balanced, and then adjust the vernier attached to the weight so as to read zero on the scale which extends along the arm of the lever. In the machine shown in the sketch (fig. 212), the weight is 30 cwts. In the Cooper's Hill College machine it is 1 ton, and the fulcrum distance—the short arm of the lever—is 4 inches. We will consider the latter. On the scale extending along the level is one division which coincides exactly with the principal knife-edge, and, if the jockey-weight is run back past this principal knife-edge to the position of – 1 division, it ought to balance a 56-lb. weight hung at a leverage of 40 on the other side of the principal fulcrum, and this is a test very easily applied. This may seem a totally unnecessary precaution, but sometimes after repairs it is by no means superfluous, and Professor Unwin states that, a weight for his first machine having been sent to be standardised, in adjusting the weight the officials forgot to take into their calculation the four little rollers on which the weight runs, and consequently the weight was made wrong, and, had he not tested it himself, might have led to serious errors.

The next calibration necessary is to test whether the fulcrum distance agrees with the unit length on the scale. The most convenient way of doing this is to have a special 1-ton weight made which can be hung in the shackles of the machine. This 1-ton weight in the shackles ought to balance the 1-ton jockey-weight at the first scale distance on the machine, or, what is still more accurate, it ought to balance a 56-lb. weight at a leverage of 40 to 1. This test of the fulcrum distance is one that ought to be applied to every testing machine from time to time.

The third test is of less importance, as the error introduced is likely to be at most only a small one, the whole movement of the lever being through a very small arc, often not more than 1°. If, however, the centre of gravity of the jockey-weight is below the line drawn through the knife-edges, then the pull on the specimen will increase as the lever moves downwards, and, if the centre of gravity of the jockey-weight is above that line, the pull on the specimen will increase as the lever moves upwards. An easy way of testing the machine is to place in the shackles an ordinary suspended weighing machine capable of registering 1 ton. This must first be balanced by the jockey-weight with the lever horizontal, and afterwards with the lever inclined upwards and downwards. It does not matter about the weighing machine being very accurate, as all that is wanted is to find the variation of the pull with the movement of the lever. Professor Unwin found, in testing his machine with a movement of the end of the lever 3 inches upwards and 3 inches downwards, that the error introduced by the movement of the lever in the pull on the specimen was 12 lbs., which, as he remarks, is practically unimportant for most testing, but, as in a badly-adjusted machine this might be much more, it should not be altogether overlooked.

The Test Piece.—The test bar may be of any convenient size, and either round or rectangular in section. For testing, a bar of circular section is distinctly the best, as it can be more accurately gauged after fracture and the contraction of area more exactly determined. The contraction is also more regular with such a section, as the mass of metal is equally distributed on all sides where local contraction commences. In the case of plates and bars, circular test bars are generally impracticable, and it is usual to test a parallel strip of plate as rolled, which may be shouldered down from each end or not.

The following sketches show the forms of test piece in common use.

They may have screwed ends, or be held in the shackles by wedge grips:—

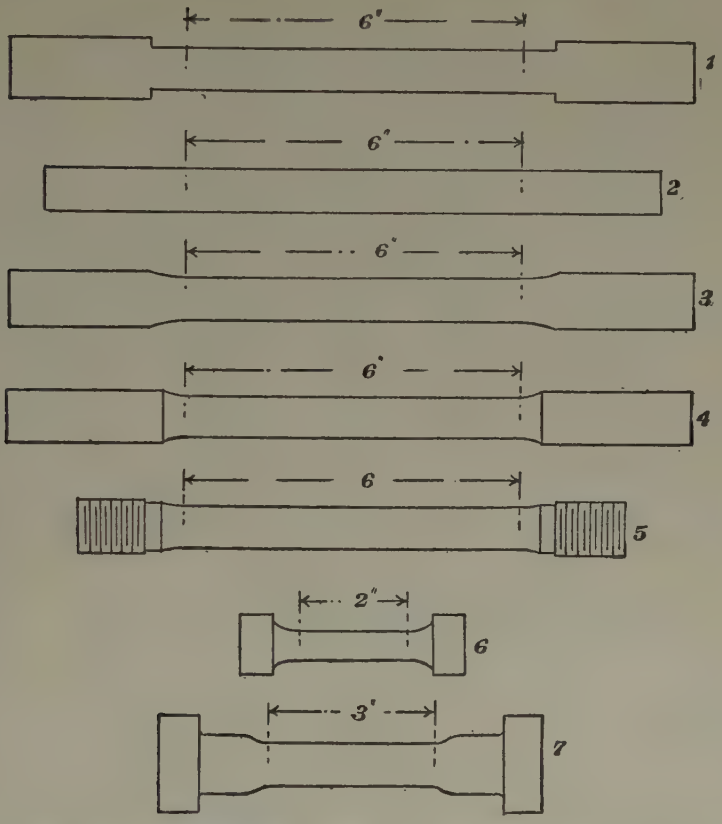


Fig. 217.—Bars for Tensile Tests.—Nos. 1, 2, and 3 are flat bars; Nos. 4, 5, 6, and 7 round. No. 1, showing sharp corners where the section is reduced is a form to be avoided; the shoulders should be shaped as shown in No. 3.

The Shape and Form of Test Piece.—That the form or shape of the test piece has considerable influence on the ultimate tensile strength, and also on the elongation, has long been known, and this was first investigated by Kirkaldy.* The most important point is to avoid any sudden change in the section of the specimen and all sharp angles should be avoided, the change from the larger section to the smaller being gradual, as shown in fig. 217, Nos. 3, 4, 5, 6, and 7.

The following sketches, which are taken from Mr. W. G. Kirkaldy's "System of Testing," very clearly show the influence of shape on ultimate tensile strength. A, which has a parallel portion with gradually-reduced section, may be regarded as the sample which gives the normal or true strength of the material; B, with the square corners, giving the lowest result; and D, with the groove, giving the highest. The results obtained with different shapes will vary considerably with the ductility of the sample, and thus

* "Experiments on Wrought Iron and Steel," and "Experimental Enquiry into the Mechanical Properties of Fagersta Steel."

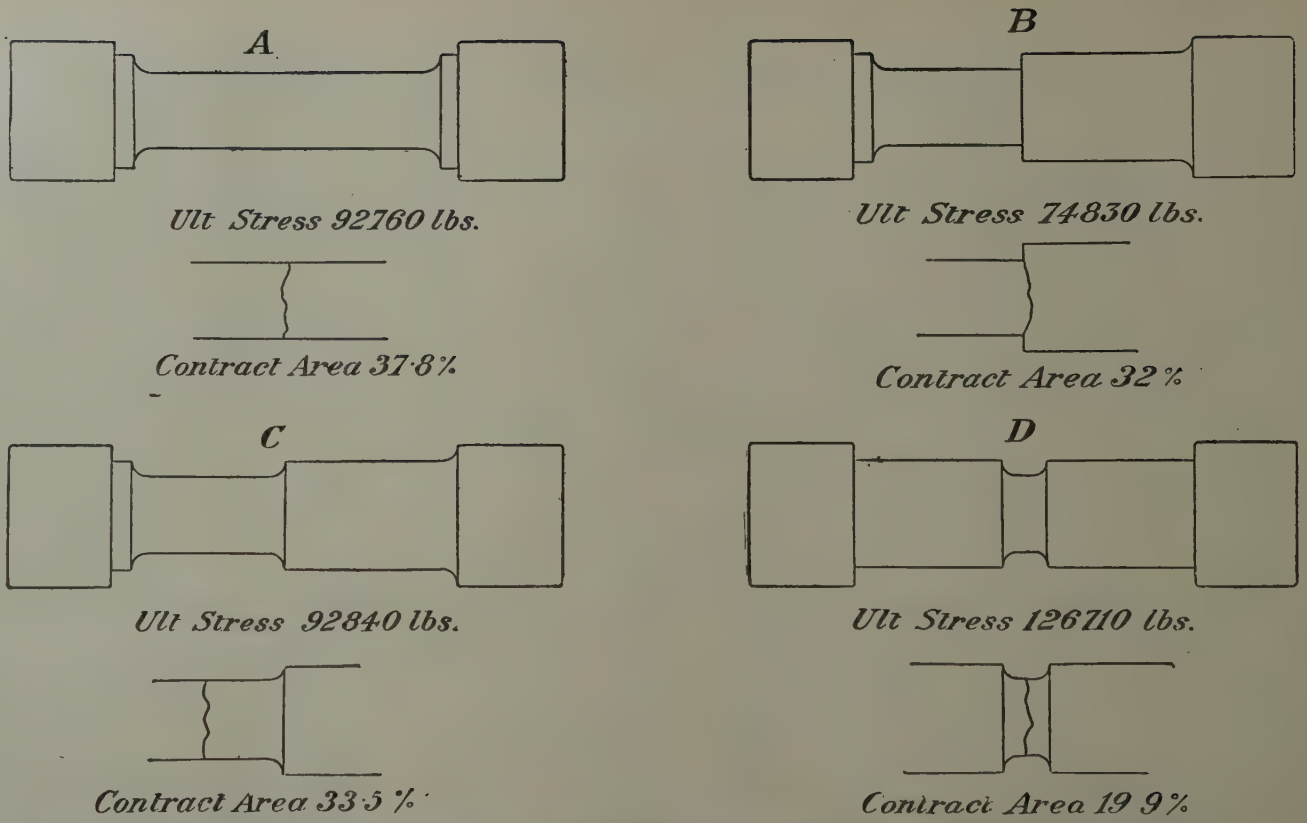


Fig. 218.—Sketches illustrating the influence of the shape of the Test Piece on the Ultimate Stress and Contraction of Area.

The Ultimate Stress of B is less than A by 17,930 lbs., or 19·3 per cent.
„ „ D is more than A by 33,950 „ or 36·6 „

the square corners will not have such a detrimental effect on mild steel as on harder metal owing to the flow of the material. In mild steel, the grooved samples, like D, will give high results, as the contraction of area which precedes fracture is prevented to some extent by the greater mass of metal near the shoulders, but in less ductile materials this influence operates to a smaller extent. In mild structural steel, the flow of metal before rupture extends over a length equal to 6 to 8 times the width of the sample, and if this natural flow is retarded in any way, the maximum breaking load will be increased. Hence it is usual to shape mild steel samples so that at least a 6-inch, and usually an 8-inch or 10-inch, length is left parallel. In harder varieties of steel, such as tires, the parallel portion is frequently not more than 2 inches.

In preparing test bars from plates, or flat bars, angles, &c., it is usually better to shoulder the sample down, leaving the parallel portion of smaller sectional area, as shown in 3, fig. 217; but very good results may be obtained by taking strips of the same sectional area throughout, and this saves some time and expense in preparing the samples. The size and form of test bars which have been adopted by Engineering Standards Committee are given with the Summary of Specifications (p. 500, *et seq.*).

Gauging the Test Piece.—The test piece having been machined to the required shape, the first thing to be done is to take its dimensions accurately. For very rough testing this may be done with a pair of calipers, but a convenient measuring instrument is the screw micrometer, shown in fig. 219. The specimen is placed between the true faces, and the

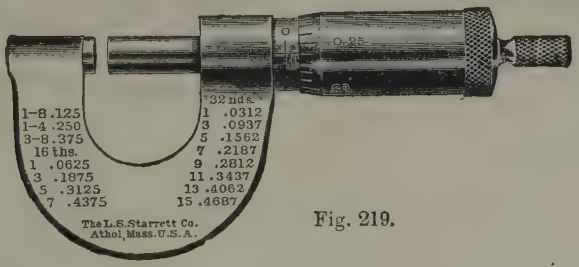


Fig. 219.

cylinder advanced by turning the sleeve by the milled head until it just touches the test piece, and there is contact without appreciable pressure. There is a graduation along the straight cylinder into tenths and quarter-tenths of an inch, and the edge of the sleeve is itself graduated into 25 divisions, each of which corresponds to the movement of the jaws $\frac{1}{1000}$ of an inch. A certain amount of delicacy of touch is required to get uniform and reliable results with this instrument, but with care it is sufficiently accurate for all ordinary purposes, although for very special scientific work it is better to employ a Whitworth measuring machine. The bar must be carefully gauged in at least three places along its length, and, if anything but a cylindrical bar, both the width and the thickness taken. These dimensions in three places are noted down, and from them the sectional area calculated, and the mean taken. A very fine line is then drawn with a scriber along the surface of the test piece, preferably along the centre of the wide side if a flat bar, and on this at any given distance two very small punch marks are made. The distance between these marks varies with the length on which it is desired to determine the elongation or extension, and may vary from 8 or 10 inches in mild steel to 2 or 3 inches in case of tires or axles.

Testing the Specimen.—The test piece is now placed in the shackles of the machine and pressure turned on until the beam lifts, when the weight is cautiously advanced along the lever beam to keep it floating in the horizontal position midway between the top and bottom stops, shown in fig. 212, on the top of small standard, *k*, at end of the beam. Assuming the specimen is a soft steel bar, when a load of about 12 to 13 tons per square inch is reached, if a pair of dividers is held on the two distance marks on the surface of the sample, the bar will be seen to stretch suddenly about $\frac{1}{100}$ of an inch, and almost immediately afterwards the beam will drop on to the bottom stop. The commencement of this elongation marks the elastic limit, and the drop of the beam the yield point, although often in commercial testing the drop of the beam is taken as the elastic limit as being more definite, and probably quite near enough for ordinary purposes. The load at the yield point is read off, and the pressure being continued the beam will rise again, and the weight will have to be advanced fairly rapidly to keep the beam floating between the stops. At about 25 to 28 tons per square inch the beam will drop again, notwithstanding that the pressure is full on and no further load is added. The reading must then be taken, as this is the "maximum stress" the bar will bear. The jockey-weight is now run back to reduce the load and keep the lever floating, as far as possible, until rupture takes place at a few tons less than the "maximum load," and this is the "breaking load" on the reduced sectional area. Between the "yield point" and the "maximum stress" the bar stretches very rapidly, and when the maximum load is about reached local reduction of area becomes marked, and the sample rapidly "necks" down at its weakest point, as shown at A, fig. 220, and breaks. When the elastic limit,

Fig. 220.—Sample of Steel before and after Fracture.

as distinct from the yield point, is required, instead of depending upon the drop of the beam, it is better for an assistant to stand with a pair of dividers on the elongation points of the specimen, and, directly an appreciable elongation takes place, to take the pressure off and see if the sample returns to its original dimension. If it does, the load can be slightly increased and pressure again taken off, and so on, until the point when permanent set takes place is determined. By this means very accurate determinations of elastic limit can be made, and any error due to the drop of the beam caused by the slipping of the sample is avoided.

Extensometers.—Although the above method gives very good results for commercial work, when it is remembered that an 8-inch length of mild steel only extends $\frac{1}{1600}$ of an inch for each increase of 1 ton per square inch, if scientific accuracy is required a much more refined method of measurement must be adopted, especially when it is desired to determine the extensions for very small increments of the load. In such work it is often desirable to be able to read any increase in length to $\frac{1}{50000}$ of an inch, and in such cases it is necessary to measure the extensions on opposite sides of the bar and take a mean of the two readings, as any slight bending of the bar would make readings from one side wholly unreliable. These measurements may be made independently by means of mirror micrometers, as in Bauschinger's experiment, but it is generally more con-

venient to make them indirectly, and several instruments, known as extensometers, have been devised for this purpose. One designed by Professor Unwin gives accurate readings to $\frac{1}{10000}$ of an inch, and more recently Professor Ewing has devised a most beautiful instrument which is capable of indicating an extension of only $\frac{1}{250000}$ of an inch in a test bar.*

The Measurement of Specimen after Fracture.—The specimen after fracture is removed from the shackles, the dimensions of the fractured ends taken with micrometer or calipers, and the reduction of area calculated. The sample is then placed on a flat slab or table, the fractured ends pressed close together, and the distance between the elongation marks measured. The increase in length then gives the elongation which has taken place in 4, 6, 8, or 10 inches as the case may be, and this can be calculated into percentage on the original length. Fig. 221 shows two samples of steel before and after testing, showing elongation and contraction of area.

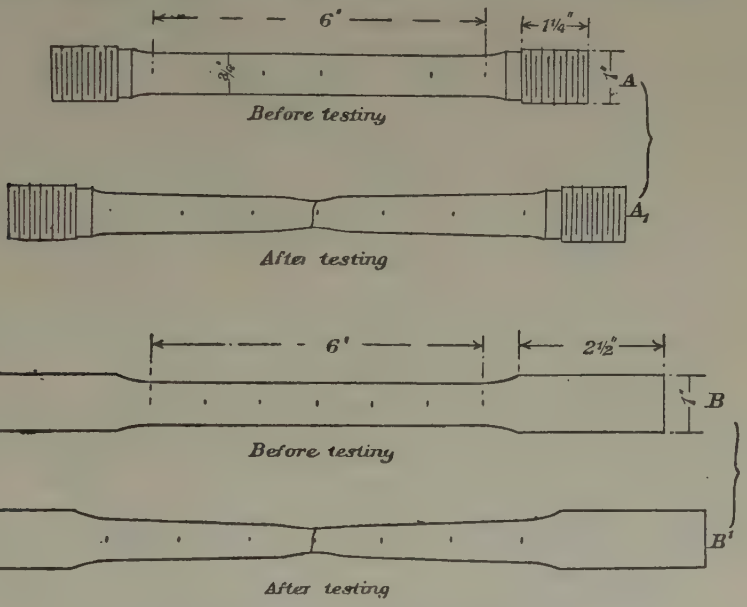


Fig. 221.—Round and Flat Bar before and after Testing.
Bars divided into inches before Testing.

In some cases it may be advisable to mark off the length of the bar into inches, as shown in the sketch, fig. 221, so that the elongation at any given part of the bar may be registered; but this is not usually done, the ultimate elongation being sufficient for ordinary purposes. The total elongation, as has already been pointed out, includes both the elongation which has occurred over the whole length of the bar and the local elongation which has taken place after the yield point has been reached, and the material is in a more or less plastic condition. The ultimate elongation is greater the more suddenly and rapidly the load is applied,† in some cases to a remarkable extent, and long continued stress maintained

* Ewing, *Testing of Materials*, pp. 75-80.
† Unwin, *Testing Materials of Construction*, pp. 89 and 90.

over a considerable period, say, for several weeks, has a most marked effect in increasing the tensile strength of the material.

The following gives the detailed observation and measurements to be made in testing an ordinary flat bar as shown in the sketches :—

Thickness, mean of 6 readings, ... = 0·4815 inch.
Width, ,, 4 ,, ... = 2·995 inches.
$\therefore$ Area = 2·995 × 0·4815 = 1·4421 square inch.

Maximum stress registered by machine, . . . = 50·83 tons.

,, ,, per square inch sectional area, . = $\frac{50·83}{1·4421}$ = 35·26 tons.

Elastic limit weight registered by machine, . . = 32·5 tons.

,, ,, per square inch sectional area, . . = $\frac{32·5}{1·4421}$ = 22·54 tons.

Contraction of area—
Thickness of plate at fracture, mean of 4 readings, . = 0·368 inch.
Width ,, ,, ,, 2 ,, . = 2·4375 inches.
$\therefore$ Contracted area = 2·4375 × 0·368 = 0·897 square inch.

The percentage of contraction in area of cross-section of the bar

$$= \frac{\text{difference between original and contracted area}}{\text{original area}} \times \frac{100}{1}$$

$\therefore$ Percentage of contraction of area in particular case under consideration will be

$$\frac{(1·4421 - 0·897) \times 100}{1·4421} = \frac{0·5451 \times 100}{1·4421} = 37·79 \text{ per cent. contraction of area.}$$

Percentage elongation—
Original length = 8 inches.
Length after fracture = 10·13 ,,

$$\text{Percentage elongation} = \frac{\text{difference between the two lengths}}{\text{original length}} \times \frac{100}{1} = \frac{2·13 \times 100}{8}$$

= 26·62 per cent. elongation in 8 inches.

A load of 1 ton on the bar produced an extension of 0·000415 inch.

The modulus of elasticity may be calculated from the following formula—

$$E = \frac{p \times L}{\omega \times l},$$

where L = original length, 8 inches, ω = original sectional area, 1·442,
p = stress, l = extension measured.

$$\frac{1 \times 8}{1·4420 \times 0·000415} = 13{,}370 \text{ tons sq. in.}$$

We thus get—

Maximum Stress.	Elastic Limit.	Contraction of Area.	Elongation on 8 inches.	Modulus of Elasticity.
35·26 tons.	22·54	37·79 per cent.	26·26 per cent.	13,370 tons.

In the case of circular or square bars, the calculations are made in exactly the same way. It is usual to describe the nature of the fracture as crystalline, partly crystalline, fibrous, finely granular, &c., according to its appearance. It is important at times to obtain diagrams showing the behaviour of the test piece while under stress, and considerable ingenuity has been shown in devising various instruments for automatically recording, by means of a curve, the elongation, elastic limit, and maximum stress. The curve given in fig. 210, p. 301 was taken by such a recorder at Cooper's Hill.

Compression Tests.—The great bulk of testing done as regards steel in the machines described consists of tensile tests, but for other metals, such as cast-iron columns, and occasionally for steel, compression tests are advisable. In testing steel small cylinders similar to those shown in the sketches (figs. 223 and 224) are taken and subjected to a gradually-

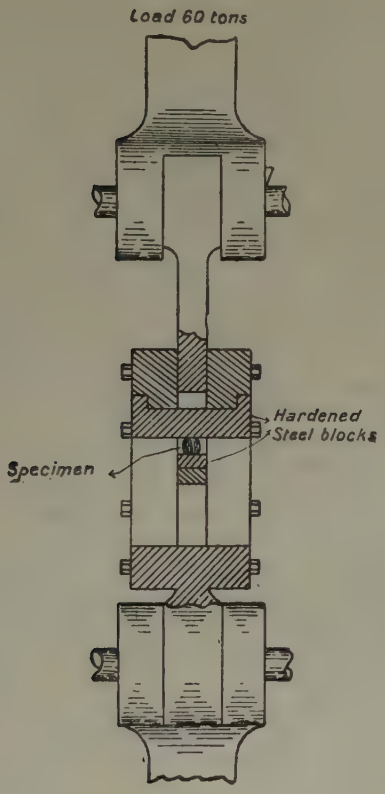


Fig. 222.

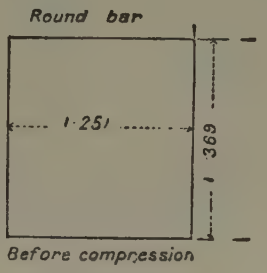


Fig. 223.

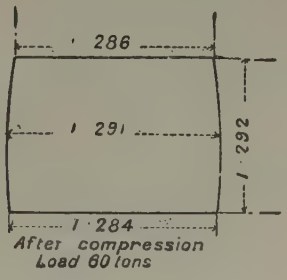


Fig. 224.

Compression Test.

increasing load, the specimen being carefully gauged before and after the experiment. Fig. 222 shows the shackle which is used at Cooper's Hill for this work, and the following results were obtained by Mr. Philip Reilly with a sample of steel :—

COMPRESSION TEST ON ROUND BAR STEEL.

Original Dimensions.		Contracted Dimensions.	
Length,	1·367	Length,	1·292
Diameter,	1·251	Diameter,	1·286 end. 1·291 middle. 1·284 end.
Area,	1·229		

Load in Tons.	Length in Inches.	Total Difference.	Total Difference × 50 for plotting.
0	1·367	0·000	0·000
5	1·366	0·001	0·050
10	1·366	...	...
15	1·366	...	...
20	1·365	0·002	0·100
25	1·365	...	...
30	1·363	0·004	0·200
35	1·356	0·011	0·550
40	1·348	0·019	0·950
45	1·337	0·030	1·500
50	1·325	0·042	2·100
55	1·310	0·057	2·850
60	1·292	0·075	3·750

Ordinary Transverse and Shearing Tests.—Transverse tests, except in the form of bending tests, are not usually made in the case of steels, although rolled joists and girders are sometimes tested in this way, and shearing stresses are also sometimes required. Fig. 225 shows one method used at Cooper's Hill in making shearing tests. It is best to have a thread cut upon the bar, A, so it can be screwed through the blocks, C, D, E, shown in the figure, as otherwise the bar is liable to bend away from them.

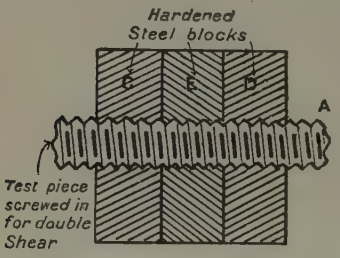


Fig. 225.—Shearing Test.

These blocks fit into a shackle similar to that used for compression, and when the pressure is put on, the centre block, E, remains fixed, and the side blocks, C, D, are forced down and shear off the ends of the sample. As both ends are sheared off, the actual area sheared is double the area of the bar, and the calculation is as follows:—

Diameter, 0·654.
Area, 0·336 square inch.
Being in double shear area 0·336 × 2 = 0·672 square inch.
Sample sheared at 19·4 tons on the beam.
Equal to 28·87 tons per square inch.

The Wicksteed machine described on p. 303 is specially designed for transverse testing of large beams, joists, and girders, and much useful information may be frequently gained as to the weak portion of any given section, and where it requires stiffening. In this machine 18-inch joists can be readily tested.

Torsional Tests are frequently made on wires, but these are rarely required for structural steel specimens. A special attachment for this purpose has been designed and is supplied by Messrs. Buckton for use with the Wicksteed machine, but is hardly of sufficient importance to metallurgists to need description here.

Variation in Strength of Specimens from same Plate, Bar, &c.—It is a well-known fact amongst practical men that if a strip be taken from a plate as rolled, cut in two, and the one tested as rolled and the other machined and then tested, that the former will give a higher ultimate or maximum stress probably owing to the more highly compressed material

on the outside. It has also been found that considerable variation may occur in material if comparative tests are taken from different parts of a large bar, the outside giving a distinctly higher maximum stress than the centre. In the following table* Campbell gives some results showing a difference of over 2 tons between the outside and the centre of forged rounds:—

TABLE LVIII.—Physical Properties of Test Pieces $\frac{3}{4}$ inch in Diameter cut from Forged Rounds.

Size of Ingot, 18 × 20 inches. Pennsylvania Steel Company, 1893.

Diameter of Forged Round.	Place from which Test was taken.	Ultimate Strength, Tons per Sq. In.	Elastic Limit, Tons per Sq. In.	Elongation in 8 Ins., per Cent.	Reduction of Area, per Cent.	Elastic Ratio, per Cent
8 ins.	At a depth of 1 inch from outside,	28·00	14·67	21·50	40·4	52·4
	At a depth of 2 inches from outside,	25·93	13·02	22·25	37·5	50·2
	The central axis,	25·93	14·05	20·25	34·1	54·2
10 ins.	At a depth of 1 inch from outside,	29·49	16·55	19·50	33·9	56·1
	At a depth of 2½ inches from outside,	28·01	15·92	18·00	32·7	56·8
	The central axis,	27·18	14·34	19·50	23·8	52·8
	Preliminary test of same heat from 6-inch ingot,	28·54	18·86	26·25	41·7	66·1

These differences may be due to some extent to variation in the chemical composition due to segregation, but as it occurs in cases where the material is of very highest quality, in which segregation would be small, such as axles and tires, this is not sufficient to explain the facts, and it is more probably due to the surface being more compressed by forging or rolling, and to the different rates of cooling of the outside and inside. Whatever its cause it shows the importance, both in the interest of engineers and manufacturers, of a general agreement as to what part of a bar a sample shall be cut from if concordant results are to be obtained. When working to specification it is usual for manufacturers to roll down a bar from a small ingot, as a preliminary test, to assist in the classification of the metal, but owing to the varying amount of work and the finishing temperature, these bars always differ to some extent, and often to the extent of 2 to 3 tons per square inch from the specimens cut from the finished section. There is no doubt that the amount of work has some influence on the strength of the material, but probably not so much as was formerly supposed. This is a matter largely within the control of the steel maker, and he must arrange to cast his ingots of such a size that sufficient work is put upon them, in producing the finished article, that they will have the required mechanical strength and soundness, although it must be recognised that it is not possible to ensure the same amount of work on large that it is on small sections.

Although the testing machine is able to afford much information as to the properties of steel for various purposes, it tells us nothing as to its

* Campbell's *Structural Steel*, p. 220.

welding qualities or its behaviour in forging or hot working at different temperatures, and only incidentally gives evidence as to its power of resisting fracture from loads applied suddenly, and consequently additional tests have often to be made.

Various tests have been proposed from time to time with a view of supplementing the information obtained by the ordinary Static method of testing, and amongst the most useful are (1) Hardness tests, (2) Impact tests on notched or plain bars, (3) Alternating impact and repeated bending tests.

Hardness Tests.—The best known method for the determination of hardness is the Brinell, which determines the resistance to penetration which the material offers when a hardened steel ball of given diameter placed upon it is subjected to a definite load. The depth of the impression is not measured

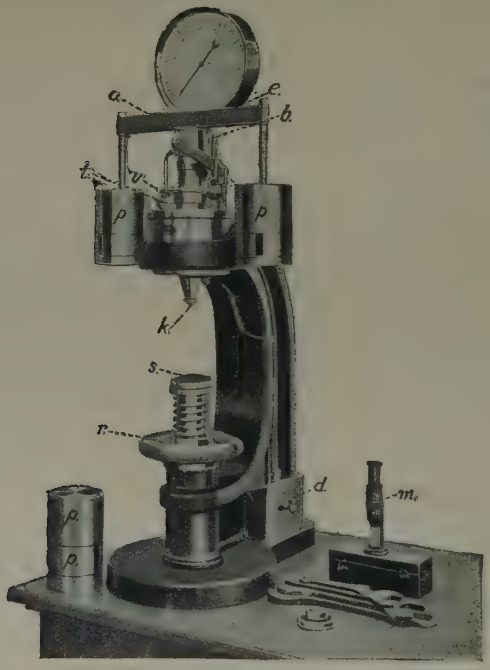


Fig. 226.—Brinell Ball Testing Machine.

direct, but the diameter of the cavity is accurately gauged by means of a microscope fitted with a millimetre scale, vernier, and crosshair. From this the spherical area is calculated, and the maximum load in kilogrammes divided by the area gives a hardness number.

Fig. 226 shows a machine specially designed for carrying out this test.

It consists of a hydraulic press acting downwards, the lower part of the piston being fitted with a 10 mm. steel ball, *k*, by means of which the impression is made on the surface of the specimen or object to be tested. The sample is placed on the support, *s*, which is vertically adjustable by means of the wheel, *r*. The table at the top of the support can be more or less inclined to enable the upper surfaces of irregular-shaped specimens to be made quite horizontal when testing. The whole apparatus is solidly mounted on a cast-iron stand.

The pressure is produced by means of a small hand pump, and is recorded in kilogrammes on a specially graduated pressure gauge.

In order to render the motion of the piston quite frictionless, packings are dispensed with, for, as the piston is so accurately fitted, they are unnecessary.

Any small quantity of fluid escaping is collected by means of a pipe conduit in a receptacle, *d*, at the foot of the stand, whence it is poured through the funnel, *t*, to the oil reservoir.

In order to guard against any error of the gauge, the machine is fitted with a special contrivance which checks the indications of the gauge, and at the same time serves to prevent any excess of pressure beyond the exact amount required, which may be varied at will from 500 to 3,000 kilogrammes by increasing or decreasing the weights, *p*.

This controlling apparatus consists of a smaller cylinder, directly communicating with the main cylinder, which is furnished with a frictionless piston. When this is loaded with weights corresponding to the amount of pressure required, the piston is pushed upwards at the very moment when the required pressure is attained.

A test specimen must be properly planished by file, grindstone, or emery wheel, on the place where the impression is to be made, and then be placed on the support, *s*, which is raised by means of the handwheel, *r*, until it comes into contact with the ball, *k*. On then closing the valve, *v*, which cuts off communication between the press cylinder and the oil cistern, and applying a few slow strokes with the hand pump, the pressure needed to force the ball downwards will be produced, thereby causing a slight impression in the sample of metal. As soon as the requisite pressure is attained, the upper piston with the controlling apparatus is forced upwards, whilst the corresponding pressure is indicated by the gauge.

On testing specimens of iron or steel, the pressure must be maintained for about 15 seconds, but in the case of softer material, during about half a minute. After the impression is made the pressure is removed, and the sample at the same time released by re-opening the valve, *v*, and lowering the support, *s*. The communication is thus restored between the cylinder and the oil cistern, and the spiral spring fitted within the cylinder, being of just sufficient strength to overcome the weight of the press piston, pulls it upwards into its original position, whilst forcing back the liquid into the cistern. The diameter of the impression produced by the ball is then measured, and the corresponding hardness numeral looked for in the table.

The best way of measuring the diameter of the depression is by using the microscope, *m*, which is specially made for that purpose, and which gives results accurate to within $\frac{1}{20}$ millimetre.

The hardness numeral is ascertained by dividing the maximum pressure by the spherical area of the concavity.

The rule for calculating the hardness numeral is as follows :—

Radius of ball, ... = r
Diameter of depression, ... = D
Superficial area of the depression in mm., . . = y
Pressure on ball in kilogrammes, ... = K
Hardness number . . . . . = H

$$2\pi r\left(r - \sqrt{r^2 - \frac{D^2}{4}}\right) = y. \qquad \frac{K}{y} = H.$$

EXAMPLE.—Let $r = 5$ mm. $D = 4$ mm. $K = 3{,}000$ kilogrammes.

$$\text{Then } 2\pi 5\left(5 - \sqrt{25 - \frac{16}{4}}\right) = 13{\cdot}13 = y \text{ and } \frac{3{,}000}{13{\cdot}13} = 228 = H.$$

Several other methods of determining hardness have been proposed, one of the most recent being the sclerometer. In this instrument a hard steel ball is allowed to fall from a definite height upon the surface of the specimen, and the height of the rebound is registered. This is said to be a measure of the hardness, and no doubt when dealing with similar material comparative results are obtained, but other properties, such as the elasticity of the body under examination have an important effect, and must be taken into consideration before drawing conclusions from results with different classes of steel.

Impact Tests.—During recent years very many methods have been devised by engineers for testing metals by impact, with a view of showing up weaknesses under sudden shocks or alternating stresses, which are not clearly indicated by the ordinary tensile tests.

The methods at present more or less used by engineers and metallurgists may be divided broadly into the following classes, according to the number and position of the notches and supports and method of applying the load.

(1) One notch in the centre of the bar: two supports: fracture effected by a series of blows of a falling weight (*Seaton* and *Jude*).

(2) One notch in the centre of the bar: two supports: fracture effected by one blow of a falling weight (*Fremont*).

(3) One notch, not necessarily in the centre of bar: one support: fracture effected by one blow on overhung portion from a falling pendulum or weight (*Izod*).

(4) Two opposite notches, not necessarily in the centre of bar: one support: fracture effected by a series of blows of a falling weight on overhung portion (*Brinell*).

(5) Same as (4), but with an arrangement for reversing the bar after every blow (*Kirkaldy*).

The following is a description of the method of applying the test in the case of methods (1), (3), and (5) :—

In the Seaton and Jude method a bar is taken, 4 inches long and $\frac{1}{2}$ inch square in section, and a V notch $\frac{1}{8}$ inch deep is cut in the centre of one side. The bar is supported on a bearing at each end, the notch being downwards, and is broken by a series of blows from a falling weight striking it on the centre. The weight and height of drop can be varied according to the metal under test. The energy absorbed in breaking the samples is calculated into foot-pounds. In the case of ductile steels requiring a number of blows, say seventy or more, the actual energy absorbed can be obtained to within one blow—that is, one-seventieth or so of the total energy—but in the case of brittle steels requiring only one to three blows, the error is still one blow, equal at least to one-third of the total, or even if one-half the last blow be taken as the breaking weight, the error would still be one-sixth of the total.

In the Izod method, the test piece is $2 \times \frac{3}{8} \times \frac{3}{16}$ in. and has a shallow V notch on one side; this is supported at one end in a clip or vice and held vertically. Fracture is effected by one blow of a pendulum striking the overhung portion, and the residual energy in the pendulum is measured by the arc through which it swings after fracturing the sample. In this

method an exact measure of the energy expended in fracturing the sample, within a very slight error, is obtained.

In the Kirkaldy method, the test piece is of the same dimensions as that used by Seaton and Jude, but instead of the V notch, it has two opposite circular grooves, each $\frac{1}{8}$ inch deep at the centre of the bar. The test bar is supported in a suitable block or vice at one end and fractured by a series of blows from a falling weight on the overhung portion, but after every blow the entire block is turned over by a cam attachment, so that blows are delivered alternately on each side of the test bar. In this method, as in the Seaton and Jude, the force required to fracture the bar is calculated into foot-pounds, and the degree of accuracy largely depends upon the number of blows which are required to produce fracture; owing, however, to the falling weight being a small one, the number of blows required to produce fracture, even in very brittle steels, is comparatively large, and consequently the error is not very considerable, and in moderately ductile steels is inappreciable.

In all the above methods notched bars are used to locate the point of fracture, and the results obtained largely depend upon the form of the notch. Even when this is made of exactly the same form with every possible care duplicate tests often give widely different results, due possibly to some slight local difference either in micro-structure or other physical conditions of the material at the bottom of the notch.

The author has recently examined the above methods of impact testing with notched bars of different classes of steels, and, in view of the irregularities disclosed when using the same machine for testing duplicate specimens of the same material, considers it to be a serious question how far methods showing such variations should be relied upon by engineers to differentiate between the physical properties of different materials. Small samples, in no case exceeding $\frac{1}{2}$ square inch section, were used in these experiments, and probably if larger bars not less than 1 inch square had been used more concordant results would have been obtained.

Several types of impact testing machines have been designed by Stanton and Bairstow* of the National Physical Laboratory, and are described in a paper read before the Institution of Mechanical Engineers, and have proved useful in the detection of brittleness and low elastic resistance in materials.

Some very interesting results of the testing of *unnotched* bars, *in the direction of their length*, so that the whole cross-section is subjected to the impact stress, were lately given in a paper read before The Society of Mechanical Engineers.† The machine is designed to fracture the bar at one blow, and the energy remaining in the tup immediately after rupture is determined by a very ingenious arrangement. The tests so far carried out have been made on commercial steels of good quality, and further experiments are in hand on inferior steels to see how far this method is capable of differentiating between steels of different quality, and the results will be watched with considerable interest.

Much work has been done by Breuil and others on impact testing, and the general concensus of opinion seems to be that to obtain satisfactory results unnotched bars will have to be employed.

* *Inst. Mech. Eng.*, Nov. 1908.

† "Comparison of the tensile, impact tensile, and repeated bending methods of testing." *Institute Mechanical Engineers*, Feb. 27, 1910. Blount, Kirkaldy, and Sankey.

Alternate Bending and Impact Testing.—The earliest form of machine was an alternating bending machine designed by Wohler, in which the test bar was fixed in a rotating chuck, a weight being suspended at the free end of the bar; by this means every revolution of the bar produced two reversals of stress, and as the bar could be rotated at a very high speed, a large number of alternations could be obtained in a given time, which could be readily recorded by a counter; the stress could be varied by increasing the pressure or weight at the end of the bar, but all Wohler's experiments were carried out with a stress below the elastic limit, which meant a great many revolutions and expenditure of much time to obtain the result from one specimen. Various modifications of this form of machine have been tried, but unless the stress is maintained below the elastic limit the results are not satisfactory, and if this is done the time required for each test is too long for the method to be adopted in every-day practice.

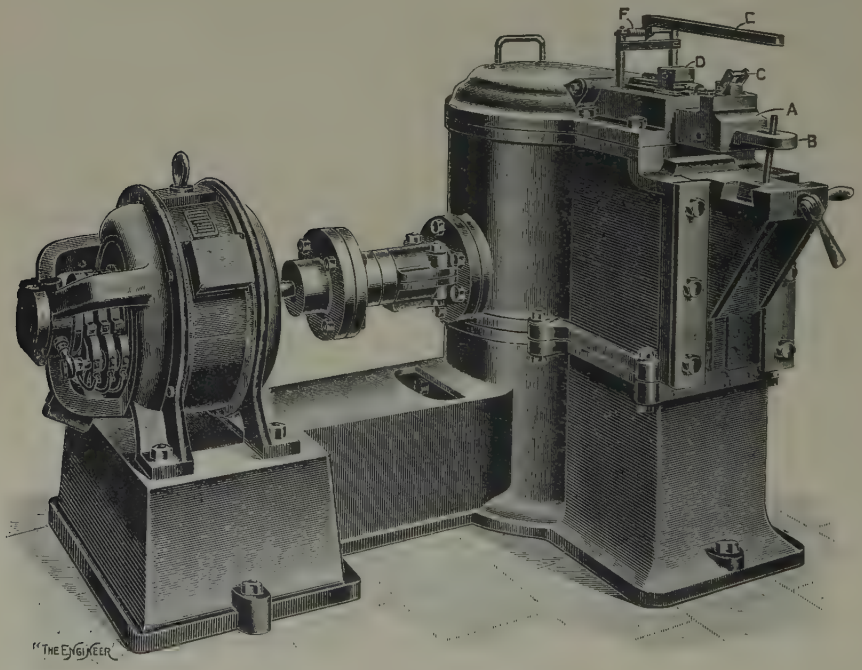


Fig. 227.—Arnold Alternating Test Machine, with Motor.—A, Ram; B, sliding plate; C, catch; D, speed counter. The bar E is attached to the test piece by a wire (not shown in the illustration), and when the test piece breaks the counting automatically stops.

Some years ago Dr. Arnold proposed an alternate bending test, in which the specimen was rapidly bent backwards and forwards through a definite angle by means of a blow, so that the test piece was not only subjected to bending, but also to shock. After a considerable number of experiments he designed a machine to carry out this test under standard conditions, and this machine with and without a motor is shown in figs. 227 and 228. A

standard bar, 6 inches long by $\frac{3}{8}$ inch diameter, is held rigidly in a die, and a slotted bar, A, moving backwards and forwards, strikes it first on one side and then on the other, and bends it through the required angle until fracture takes place, the number of alterations being recorded by a speed counter, D, which automatically stops when the sample breaks.

The standard conditions which have been adopted are as follows:—Rate of alterations, 650 per minute; distance from plane-cutting zero of bending moment to plane of maximum bending moment or stress, 3 inches; deflection at zero of bending moment, $\frac{3}{8}$ of an inch each way; size of test piece polished bars, 6 inches $\times$ $\frac{3}{8}$ inch diameter. The plane of maximum bending moment is the face of the die, and the zero of bending moment is in a horizontal plane through the point of contact of the test bar with the slotted bar. Prof. Arnold states that, given even texture, results agree to within two (or even one) alteration, and the slightest difference in the texture

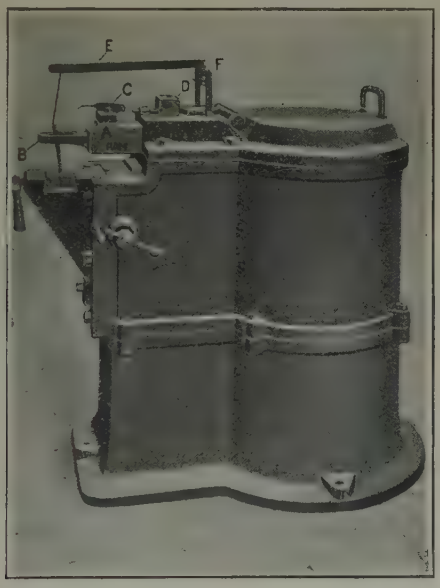


Fig. 228.—Arnold Alternating Test Machine.

of a steel is shown either by the grey tension line in the fracture being off the zero of stress in the plane of maximum bending moment, or in very bad cases by the rupture taking place above the plane of maximum bending moment or stress, as much as $\frac{1}{2}$ an inch above the die line.

Captain Sankey * has recently designed an alternate bending machine, which not only automatically records the number of bends before fracture, but the bending effort of each bend. The machine, illustrated in fig. 230, and diagrammatically in fig. 229, consists of a small bed-plate arranged to bolt down to a bench, at one corner of which there is a grip, A, for securing one end of a flat steel spring, B. The other end of the spring is fitted with

* *Inst. Mech. Engineers*, "Comparison of tensile, impact tensile, and repeated bending methods of testing steel," by Blount, Kirkaldy, and Sankey, May 27, 1910.

a special grip, C, for holding one end of the test piece, D. The other end of the test piece is fixed into a handle, E, about 3 feet long, by means of which it is bent backwards and forwards through the "standard" angle. An indicator, F, is provided to show this standard angle. Alongside of the spring, and fixed to the bed-plate, there is a horizontal drum, G, to carry the recording paper, and the pencil, H, has a horizontal motion actuated by the motion of the grip, C, and conveyed by the steel wires, L and M, and the multiplying pulley, N, the wires being kept taut by the spring box, O. The zero line is in the middle of the paper, and the pencil, H, moves in one direction when the bending is from right to left, and in the opposite direction when it is from left to right. The drum has a ratchet wheel, K, with a detent (not shown) worked by the motion of the pencil carrier. The result of the combined

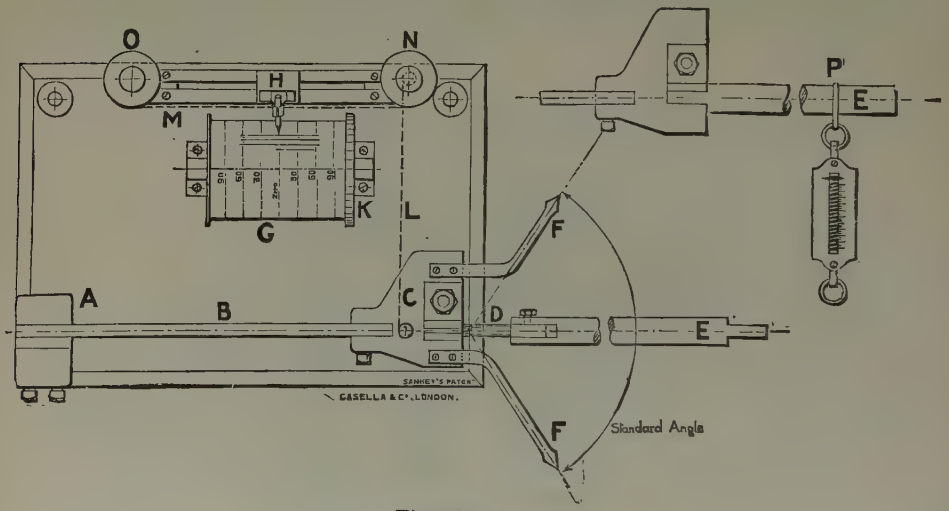


Fig. 229.

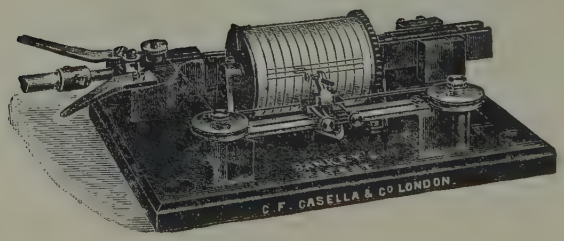


Fig. 230.

motion of the pencil and of the drum is to produce an autographic diagram. Obviously the greater the stiffness of the test piece the more the flat spring, B, will have to be bent before its resistance is equal to the resistance to bending of the test piece. Hence the motion of the pencil is proportional to the effort required to bend the test piece.

Working the Machine.—The test piece is properly secured in the handle, E (fig. 229), by means of the set screw, it is then inserted into the grip, C, and the free length ($1\frac{3}{4}$ inches) is adjusted by means of a gauge provided for

the purpose, after which the grip, C, is tightened. The first bend is taken to the left until the mark on the handle coincides with the pointer indicating the "standard" angle. The bending is then reversed, and the test piece is bent until the mark on the handle coincides with the second pointer. The bending is again reversed, and so on until the specimen breaks. The point at which the test piece breaks should be noted in decimals of one bend, which are marked on the indicator.

Calibration.—The record papers are graduated in pounds-feet, and to calibrate the machine the flat end of the lever is to be inserted in the jaws of the grip with the shoulder well up against the face of the grip, a blank chart should be placed on the drum, and the pencil set with its point on the zero line. A reliable spring balance is then attached to the peg provided for the purpose at the other end of the lever, and such pulls applied as may be necessary to cover the range of readings on either side, noting in each case the point reached on the paper by the pencil. Thus, if a pull of 20 lbs. is applied, the bending effort exerted is $20 \times 3 = 60$ pounds-feet, since the lever arm is 3 feet, and in this case the pencil point should be exactly on the 60 pounds-feet line. Should the points reached by the pencil on the chart not coincide with the pulls applied to the end of the lever, adjustment is to be effected by altering the position of the side spring plates placed on either side of the main spring. Each side should be adjusted independently. The calibration should be made after the wire has been adjusted by means of the spring box. This is important, because the calibration depends on the tautness of the wire. After inserting a new wire, the calibration should be repeated a few times until the wire has taken a permanent set.

The "standard" angle is so fixed that the distance travelled along the arc of the circle 1 foot radius from the point of bending the test piece is 1·60 feet (this angle is $91\frac{1}{2}°$). Hence, by multiplying the bending effort (in pounds-feet) by 1·6, the energy (in foot-pounds) required to make a complete bend, is found.

Generally, the stronger the material the less the number of bends it will endure, and approximately it may be assumed that, in the case of mild steel, the bending effort of the first bend is proportional to the yield stress in tension of the material. It has been found by experiment that with the standard test piece ($\frac{3}{8}$ inch diameter) one-half of the bending effort in pounds-feet is nearly equal to the yield stress in tons per square inch. This rule is only approximate, but will give a fair idea of the strength of the material as expressed in the ordinary way. The number of bends is proportional to the ductility of the material, and experiment shows that this number is approximately proportional to the elongation multiplied by the reduction of area in a tensile test.

The area of the autographic diagram represents the energy required to break the test piece. The recording gear has been so proportioned that 1 square inch of this diagram is equivalent to 400 foot-pounds. The area in question can be obtained by means of a planimeter, but it can also be approximately arrived at by estimating the average bending effort, and multiplying by 1·6 times the number of bends. 1·6 times the number of bends must be taken, because, as already pointed out, the arc swept by the point of application of the bending effort (in pounds-feet) is 1·60 feet for each bend. This energy figure gives valuable information as to the quality of the material, and for machinery steel should not be less than 2,500 foot-pounds, but for the steel used in petrol engines and the like, a higher figure is desirable, say 3,500 to 4,000 foot-pounds.

This method of testing is hardly out of the experimental stage, but is of considerable interest, as it is the first machine designed to record, not only the number of bends, but the bending effort of each bend.

Test for Welding and Hot Working.—A very useful test is to take two pieces of the material about 1 inch square and weld them together, as shown at *a*, *b* in the sketch (fig. 231). A $\frac{1}{2}$-inch to $\frac{3}{4}$-inch hole is then punched at *c*, and while still at a full red heat this hole is ex-

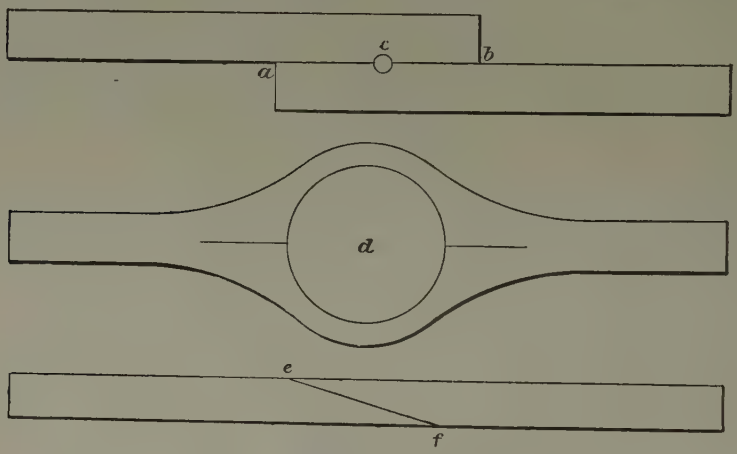


Fig. 231.—Welding and Drifting Tests.

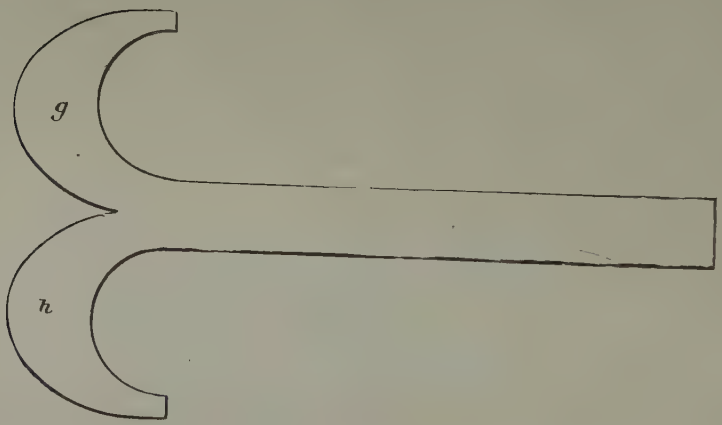


Fig. 232.—Plating-out or Rams-horn Test for Red Shortness.

panded by means of taper drifts until it is about $2\frac{1}{2}$ inches in diameter, or nearly three times the cross-section of the specimen. The sample should show no sign of opening in the weld, and the edges of the expanded portion should be free from cracks and perfectly smooth. Another test for welding is to weld two pieces as shown in fig. 231 at *e*, *f*, and while still hot bend the sample backwards and forwards five or six times across the weld, noticing if the weld show any signs of opening.

Samples should also be hammered or plated out very thin, at different temperatures, to see if there are any signs of cracking at the edges, and what is known as the rams-horn test is sometimes used. It consists in hammering on an anvil one end of a bar from a welding temperature to dull redness until it is about $\frac{1}{8}$ of an inch thick, and then cutting down the centre of the plated-out portion, reheating and bending the two pieces, *g* and *h*, backwards, as shown (fig. 232). The edges should be smooth and free from cracks. When the material is required for boiler plate the above tests are excellent for testing its working qualities.

A cold bending test, either in a bending machine or by means of a hand or steam hammer, is also often made, and it is usually specified that the sample shall be bent over a round bar $2\frac{1}{2}$ times the thickness of the sample, and shall bend over parallel without fracture. In the case of dead soft material it should not only bend over parallel but stand hammering over close without fracture, and sometimes it is specified that, previous to bending, the sample must be quenched in water from a red heat, to make sure that the steel is not appreciably hardened by quenching. The above tests are applicable to all structural materials, such as plates, channels, angles, &c.

Testing Rails, Axles, &c.—A test very largely used for rails, tires, &c., is the falling weight or drop test, and it is one of the most useful of practical tests employed. It consists in allowing a weight to fall from a specified height a certain number of times on to the sample. In the case of axles and rails these are placed on bearings a certain distance apart, and the weight is allowed to fall on to the centre of the specimen, the deflection being noted after each blow. For axles the falling weight test varies according to the views of the engineer. For engine axles it varies from a 1 ton weight falling 30 feet, five times, to a 1 ton falling 25 feet, sixteen times, the axles resting on bearings usually 3 feet 6 inches apart, and being reversed after each, or each alternate, blow. They must after this treatment show no signs of failure, but the deflection will, of course, vary with the diameter of the axle. Figs. 233 and 234 are sketches of a machine used for testing axles by the falling weight. If equal deflection is desired the weight can be kept constant and the drop varied according to the following rule:—*

Drop varies as (diameter at centre)^3.

Thus, starting with an axle $4\frac{3}{4}$ inches diameter at centre, and 1 ton falling 20 feet six times as a standard, the drop for 1 ton on to $4\frac{1}{4}$ inches diameter axle will be—

$$\frac{h}{H} = \frac{d^3}{D^3} : h = \frac{(4\frac{1}{4})^3 \times 20}{(4\frac{3}{4})^3} = 14{\cdot}33 \text{ feet.}$$

This rule is said to give excellent results, and the following table is a record of a few typical drop tests showing the amount of deflection with each blow: the axle was reversed after each alternate blow:—

Diameter.	Weight.	Fall.	1st Blow.	2nd Blow.	3rd Blow.	4th Blow.	5th Blow.
Ins.		Ft. Ins.					
$4\frac{3}{4}$	1	20 0	3 -$3\frac{1}{4}$	Straight.	$2\frac{1}{8}$-$2\frac{3}{8}$	Straight.	$2\frac{7}{8}$·3
$4\frac{1}{2}$	1	17 6	$3\frac{1}{4}$-$3\frac{5}{8}$	Do.	$2\frac{3}{8}$-$2\frac{5}{8}$	Do.	$2\frac{3}{4}$-$3\frac{1}{8}$
4	1	12 0	$3\frac{1}{4}$-$3\frac{3}{4}$	Do.	$2\frac{1}{2}$-$2\frac{3}{4}$	Do.	$2\frac{7}{8}$-$3\frac{1}{16}$

* *Engineer*, July 22, 1898, p. 75.

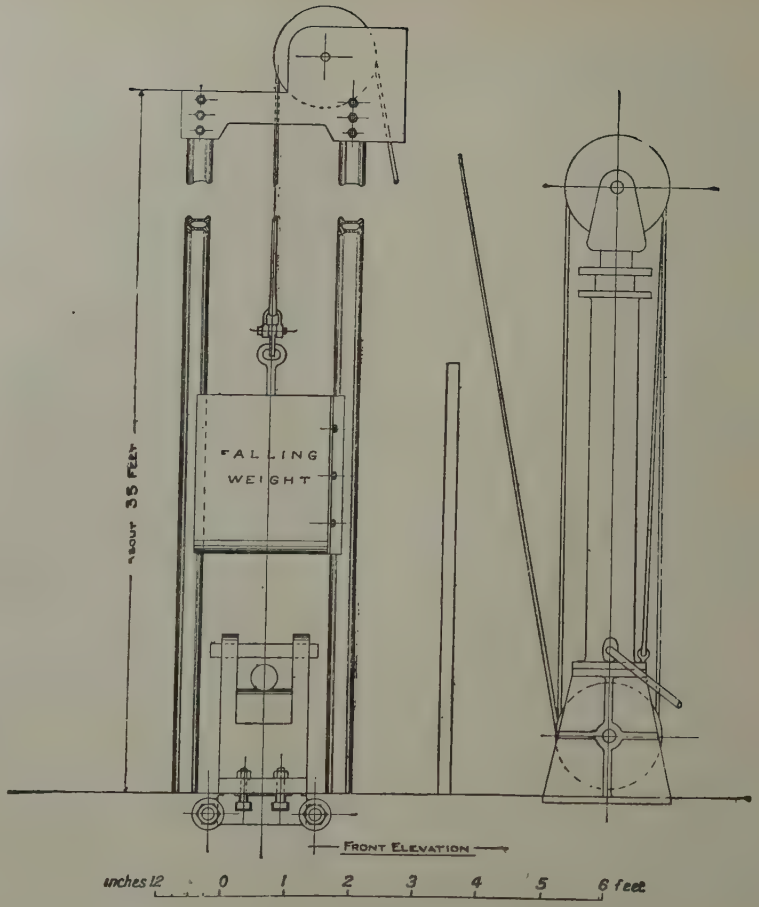


Fig. 233.—Drop-Testing Apparatus for Axles.

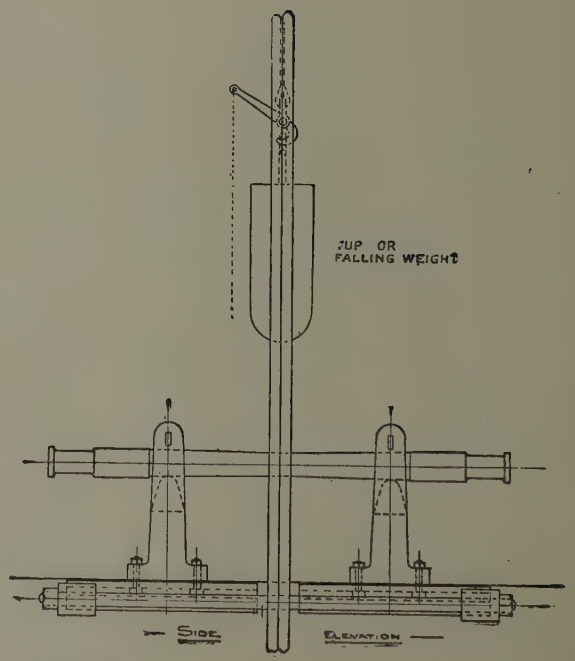


Fig. 234.

TABLE LIX.—Falling Weight of One Ton.

Description.	Material.	Dia.	D op.	1st.	2nd.	3rd.	4th.	5th	6th.	7th.	8th.	C.	P.	S.	Si.	Mn.	Elong. 4 In.	Red. of Area.	Ultimate Stress.
		In.	Ft. In.	In.	In.	In.	In.	In.	In.	In.	In.								Tons per Sq. Inch.
Engine, . .	Siemens, . .	5	30 0	3⅛	Str.	3	Str.	2⅞	Str.	2¾	Str.	·27	·03	·02	·19	·50	23	42	32·84*
,, . .	,, . .	6¾	30 0	½	Str.	¾	⅛	¾	Str.	⅝	Str.	·41	·04	·02	·26	1·05	26	50	35·70*
Carriage, . .	,, . .	4¾	30 0	3¼	⅛	2⅞	¼	2½	½	...	...	·32	·05	·09	·07	1·1	22	42	32·66†
,, . .	,, . .	4¾	30 0	3¾	¼	2⅞	½	3¼	¼	3	⅝	·33	·04	·05	·03	1·01	22	36	30·70*
Waggon, . .	Bessemer, . .	4¾	20 0	3⅛	¼	2⅜	¼	2¾	¼	...	...	·29	·04	·05	·09	1·08	25	50	35·0*
,, . .	,, . .	4½	17 6	3½	¼	2¼	¼	3¼	¼	...	...	·27	·04	·05	05	·88	23	42	32·5*

* Close good. † Close broke.

TABLE LX.—Axles Failing under Test. Also Faulty Composition.

Description.	Material.	1 Ton Falling.	1st.	2nd.	3rd.	4th.	5th.	6th.	C.	P.	S.	Si.	Mn.	Elong. 4 In.	Red. of Area.	Ultimate Stress.
		Feet.	In.	In.	In.	In.	In.									Tons per Sq. Inch.
Waggon, . .	Bessemer, . .	20	3¼	¼	2¼	Str.	3	Broke	·25	·04	·11	·07	·95	26	50	32·84
,, . .	,, . .	20	3¼	¼	2⅜	¼	Broke	...	·24	·04	·09	·05	·99	23	50	30·0
,, . .	,, . .	18	3⅜	Broke	...	...	...	...	·28	·04	·10	·06	1·07	21	54	33·7
,, . .	,, . .	18	3	¼	2⅛*	¼	2¾	Broke	·27	·03	·10	·03	1·03	24	38	30·0
Foreign makers,	,, . .	20	3¼	Str.	3	Str.	3¼	Str.	·34	·06	·07	·23	·63	25	43	39·6
	,, . .	20	2¾	Str.	2⅜	Str.	2½	Str.	·32	·04	·16	·16	·74	3 In. 29	...	34·0

* Journal flew off at third blow.

The figures in columns marked 1st, 2nd, 3rd, &c., give the deflection under each blow of the falling weight, the axle being reversed after the first and then every alternate blow.

The axle after standing the drop test is nicked and broken, and tensile and bending samples are taken from it, such samples being cut out as far as possible away from the fracture.

Tensile tests are nearly always specified for axles, and these will vary with the kind of axle—*e.g.*, a straight or a crank axle and with the composition of the steel. Specifications of various engineers are given in the Appendix. In the case of rails tensile tests are rarely asked for, the drop test, with chemical analysis, being generally considered sufficient.

Sometimes axles are deflected to 90° under the falling weight and afterwards bent under the hammer until the ends touch, as shown in fig. 235. Crank axles cannot be tested under the falling weight and bending tests, tensile and sometimes bar tests have to be relied upon. The latter consist in taking a bar 9 inches long, $1\frac{1}{4}$ square, cut from the crank, placing it on bearings 6 inches apart, and giving it twelve blows with a 10-cwt. tup falling 7 inches, the bar being reversed after each blow. The test pieces in crank axles are either cut from A, as shown in the sketch (fig. 236), or from a piece, B, forged for this purpose on the end of the crank journal.

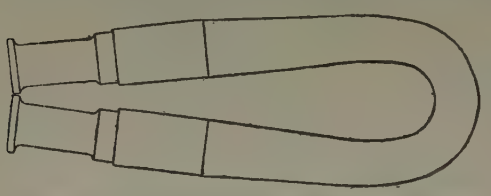


Fig. 235.—Axle bent under Drop Test and Hammer until the Ends touch.

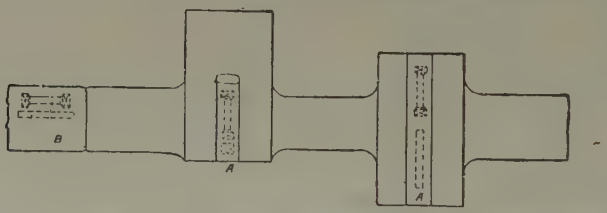


Fig. 236.—Crank Axle, showing Position from which Tensile Test Pieces are usually Slotted.

Tables lix. and lx., from Mr. Glover's article in the *Engineer*,* give the results of some good and bad axles under drop test, with the chemical composition and tensile tests.

Tire Testing.—It is usual to have pieces cut from the tires selected by

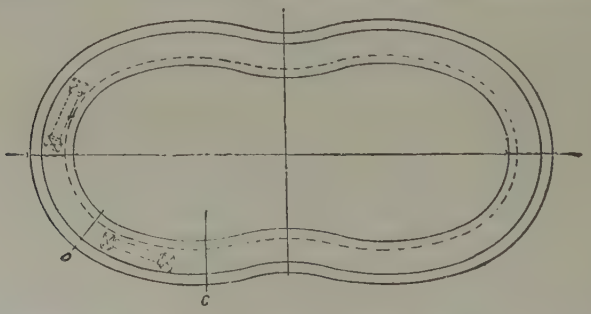


Fig. 237.—Tire after Drop Testing.—Samples for Tensile Tests are usually slotted from the portion of the Tire which is least distorted; positions as shown in sketch.

* *Engineer*, July 22, 1898, p. 76.

the inspector and tested for tensile strength, elongation, &c., and in some cases bending and drift tests are made. The falling-weight test, however, is the one which is almost universally applied, whether the others are or not, and consists in placing a tire in the *running position* and compressing it, as shown in Fig. 237, either by means of a falling weight or in a hydraulic press. Figs. 238 to 239 are sketches of a tire drop-testing machine, which is used at the Blochairn Works of the Steel Company of Scotland, for which I am indebted to the General Manager, Mr. Clark; this type of machine is used in most works, the press being comparatively little employed.

The tire is generally subjected to repeated blows of a weight of 20 cwts. falling through 10 feet, 15 feet, 20 feet, 25 feet, and 30 feet, until it is deflected $\frac{1}{8}$ of its external diameter, and any tire which cracks before the required deflection is reached is rejected. The amount of deflection required varies with the class of tire, whether carriage, engine, or waggon, and some engineers stipulate for a deflection equal to $\frac{1}{8}$ of the external diameter. The American Standard Specification specifies that the tire shall be subjected to successive blows from a 1 ton weight, falling from increasing heights until it shows a minimum deflection equal to $D^2 \div (40\,T^2 + 2\,D)$, the letter "D" being internal diameter, and the letter "T" thickness of the tire at the centre of the tread. If the tire stands the falling-weight test satisfactorily, it is nicked and broken, and the fracture examined; samples are then cut out for tensile tests, and, when required, cold bending and drift tests.

The following table gives the results of the drop testing of a number of tires of different diameters, and it will be noticed what an important influence the diameter has upon the stiffness of the tire, as indicated especially by the two engine tires, which are of identical sections, the larger tire giving nearly double the deflection of the other:—

TABLE LXI.—Average Tests. Various Classes of Tires.*

Description.	Material.	Dia.	Analysis.					Tensile.			Falling-Weight Test.									
			C.	P.	S.	Si.	Mn.	Elong. p.c. in 4 In.	Red.	Ultimate Stress.	10 Ft.	15 Ft.	20 Ft.	25 Ft.	30 Ft.	30 Ft.	30 Ft.	30 Ft.	30 Ft.	30 Ft.
		Ft. In.									In.	In.	In.	In.	In.	In.	In.	In.	In.	In.
Engine,	Siemens,	5 1	·62	·04	·02	·28	·55	16	25	50·1	$\frac{3}{4}$	$2\frac{1}{4}$	$3\frac{3}{8}$	$5\frac{1}{8}$	$6\frac{1}{2}$	8	$9\frac{3}{8}$	$10\frac{5}{8}$	$11\frac{3}{4}$	13
,,	,,	3 0	·50	·06	·02	·10	·91	16	24	43·2	$\frac{1}{8}$	$\frac{1}{2}$	$1\frac{1}{4}$	$2\frac{1}{8}$	$3\frac{3}{16}$	$4\frac{9}{16}$	$5\frac{1}{4}$	$6\frac{7}{8}$	$7\frac{7}{8}$	...
Carriage,	,,	3 0	·46	·04	·05	·16	·76	19	20	40·7	$\frac{1}{2}$	$1\frac{3}{8}$	$2\frac{3}{4}$	$4\frac{1}{4}$	$5\frac{5}{8}$	7	...	...	...	...
Waggon,	,,	2 8	·38	·04	·05	·19	1·20	19	36	39·6	$1\frac{1}{4}$	$3\frac{1}{8}$	$4\frac{5}{8}$	$5\frac{3}{4}$	7	...	...	...	...	...
,,	,,	2 8	·37	...	...	...	...	21	38	42·8	Compressed; 8-inch deflection.									
,,	Bessemer,	2 8	·34	...	...	...	...	17	24	39·5	$1\frac{1}{2}$	$3\frac{1}{4}$	$5\frac{1}{4}$	$7\frac{1}{2}$	...	...	...	...	...	...
,,	,,	2 8	·33	·04	·07	·08	1·31	22	45	40·4	Compressed; 8-inch deflection.									
			Bending.					Drift.												
Engine,	Siemens,	...	·52	·05	·03	·18	·81	15	23	46·6	53° broke.					$1\frac{1}{2}$ in. cracked.				
Waggon,	Bessemer,	...	·31	·03	·04	·09	1·23	21	32	41·8	180° ,,					$1\frac{1}{2}$ in. good.				

Generally one tire from each cast of steel is selected for drop testing, and, in the event of failure, another tire is frequently tested by the engineer before condemning the entire charge. Sometimes tires fail owing to local

* *Engineer*, July 1, 1898, vol. lxxxvi., p. 1.

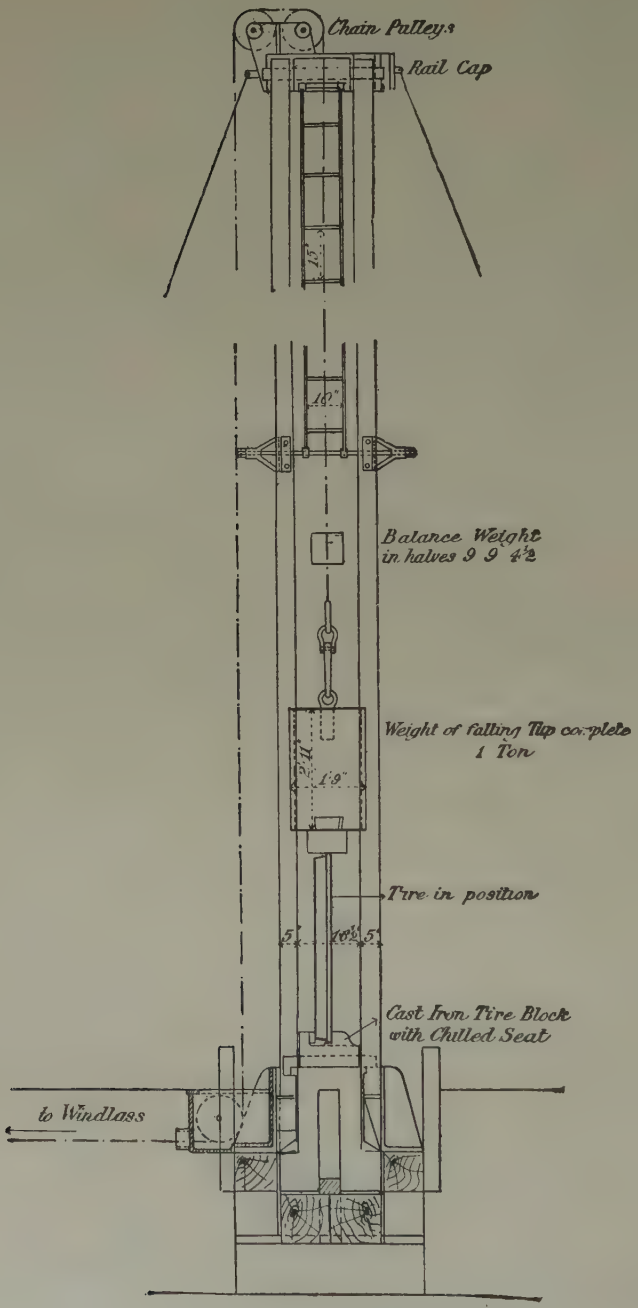


Fig. 238.— Drop Testing Machine for Tires

Fig. 239.

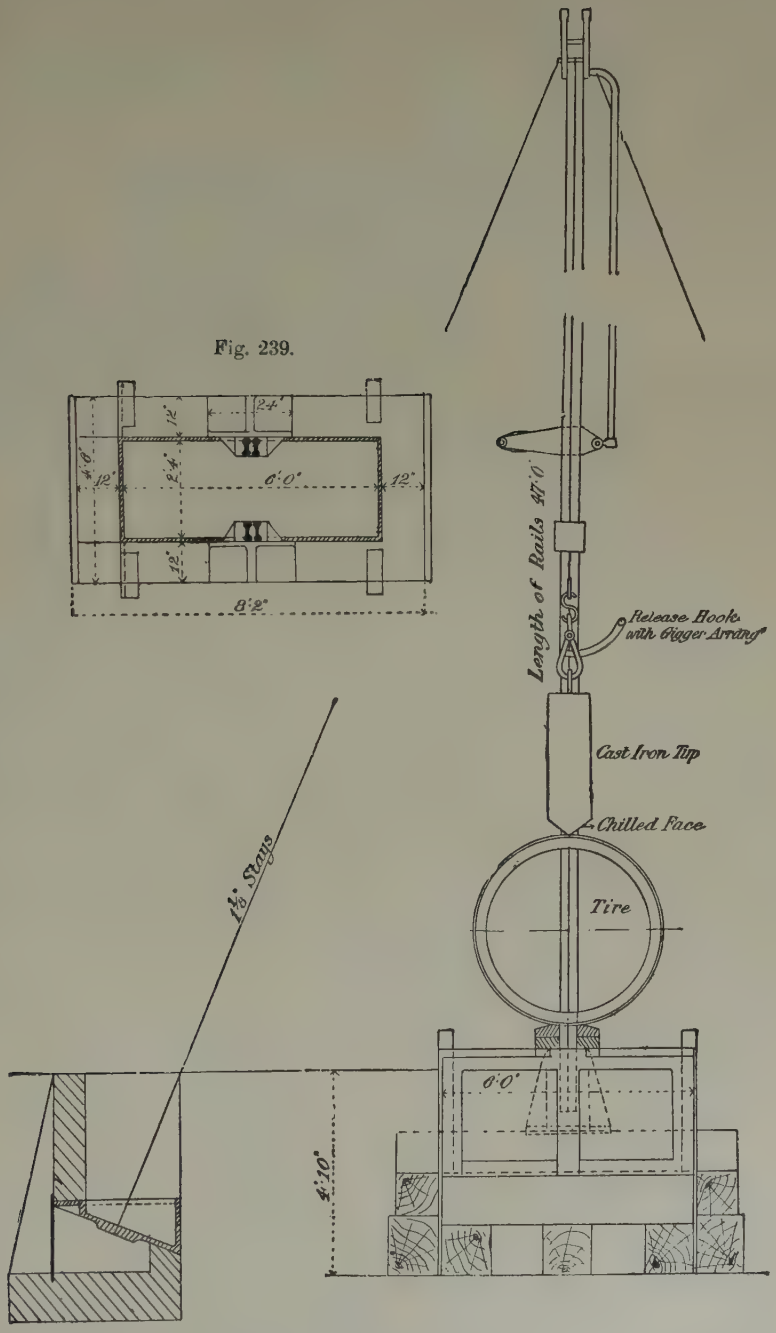


Fig. 240.—Drop Testing Machine for Tires.

chilling during manufacture, and these usually show a finer crystalline structure near the edge of the fractured surface. In such cases annealing will restore the ductility and enable them to stand the tests. This will, of course, have a general softening effect, reducing the tensile strength and increasing the elongation and reduction of area. In the following table, some results obtained by annealing are given :—

EFFECT OF ANNEALING ON WAGGON TIRES.*

Material.	Carbon.	Unannealed.			Annealed.		
		Elong. per cent. in 4 Inches.	Reduction of Area.	Ultimate Stress.	Elong. per cent. in 4 Inches.	Reduction of Area.	Ultimate Stress.
Bessemer, . .	...	13	18	48·7	25	50	41·9
,, . .	...	12	14	43·9	23	56	40·3
Siemens, . .	·38	18	34	38·6	28	42	35·7
,, . .	...	8	11	42·3	21	47	31·6

EFFECT OF CHILLING (TEST PIECE CHILLED AFTER CUTTING).

		Normal.			Chilled.		
Siemens, . .	...	25	47	38·6	...	nil	65·7

EFFECT OF OIL HARDENING (WHOLE TIRE TREATED).

		As Rolled.			Oil Hardened.		
Siemens, . .	...	19	29	36·4	23	35	38·9

The tensile tests have always to be made on short pieces on account of the curvature of the tire, usually parallel lengths of 2, 3, or 4 inches, being taken for the elongation.

Different engineers specify different limits for these tests, some preferring a harder material than others, as will be seen from the specifications given in the Appendix.

Springs.—Although springs may be used for numerous purposes the great bulk are required for railway work, and are either laminated, spiral, or volute. Generally no tensile tests are required, although some engineers specify these; most are content with some form of compression test coupled with a chemical analysis. In case of laminated springs, one or two bars are chosen out of every 100 before the spring is manufactured. These should be 30 inches long, and are cambered to a radius equal to eighty times the thickness of the bar, and then tempered to suit the particular class of spring. They are then scragged straight once, when the loss in camber should vary from $\frac{1}{8}$ to $\frac{1}{16}$, and on scragging straight again six times there should be no further loss. After the springs are fitted they are usually tested in a steam scragging machine similar to that shown in the sketch (fig. 241). In this machine, by means of an eccentric valve motion,

* *Engineer*, July 1, 1898.

the length of stroke can be varied to any required extent. The following tests, according to Mr. Glover,* are those more generally specified for laminated, volute, and spiral springs, the particular test selected depending upon the engineer:—(1) They may be scragged either straight or until half the camber is removed; or (2) until the spring is deflected 1 inch per foot

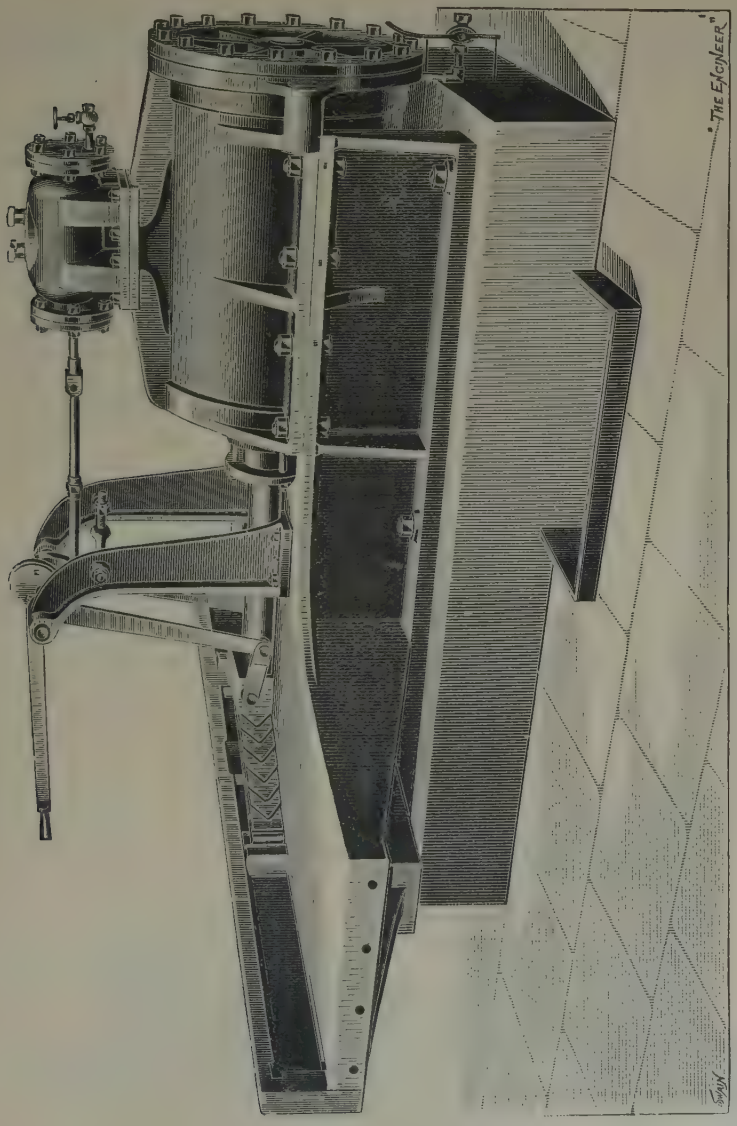


Fig. 241.—Spring Scragging Machine. From the *Engineer*, Aug. 5, 1898.

of span. Thus a carriage spring 7 feet long must deflect 7 inches, and a short stiff engine spring 3 feet 6 inches long must deflect $3\frac{1}{2}$ inches; or (3) a load 40 to 50 per cent. in excess of working load may be applied. In

* *Engineer*, August 5, 1898, p. 130.

Fig. 242.

Fig. 243.

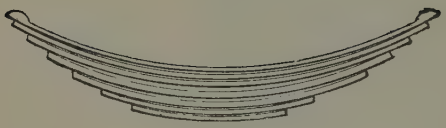


Fig. 244.

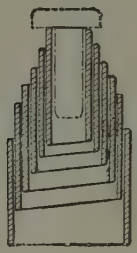


Fig. 245.

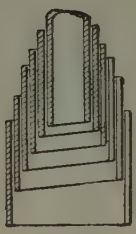


Fig. 246.

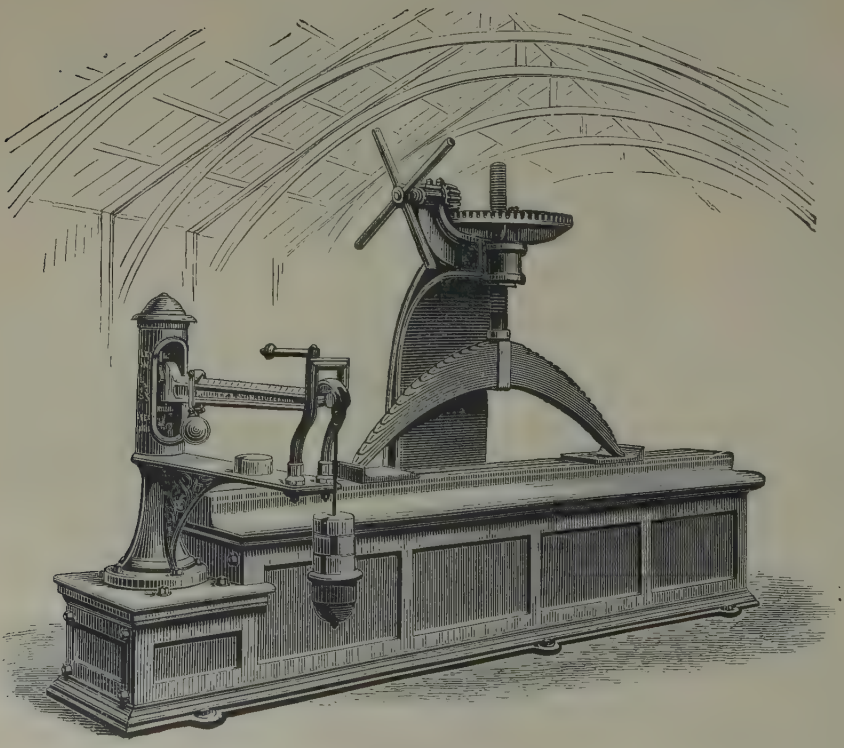


Fig. 247.

all these cases the spring must resume its former camber when the load is removed, which camber should not be more than $\frac{1}{4}$ inch above that specified for engine and carriage-bearing springs, and $\frac{1}{2}$ inch above for carriage and waggon buffer springs; nothing is allowed below specified camber in any case. Long springs when scragged should come up in one regular curve, fig. 242, and not as fig. 243, which shows want of evenness in tempering.

After scragging, springs are inspected for workmanship; the plates should bear on each other at the points. A good plan is to undo one spring in every twenty-five or so, in order that this may be clearly shown (fig. 244), also the plates when bolted up should fit closely together along their whole length, any open spaces meaning bad setting. All plates split at the ends should be rejected.

In testing volute or spiral springs, they are usually compressed solid several times, and should then not lose more than $\frac{1}{16}$ inch camber, and when released should not be more than $\frac{1}{8}$ inch above—nothing below—the specified camber. In compressing volute springs it is sometimes advisable to put a pin with turned head (fig. 245) into the top scroll in order to prevent buckling or distortion (fig. 246).

A good test for uniformity of temper in a batch of springs is to specify a minimum load when the springs are scragged straight or to the maximum deflection. A weighting test is taken occasionally from each sort of spring; increasing loads are applied and the deflection noticed after each increase of weight. Fig. 247 shows a compact machine copied from *Engineering*, in which such tests are carried out; it is made by Messrs. Pooley, of Liverpool, and is suitable for any class of spring—spiral, volute, or ordinary laminated. The pressure is applied by screw gear, in this case shown as worked by hand, but in most cases driven by belting. Table lxii., from Mr. Glover's paper, gives the results of tests as carried out in such a machine.

Spring case buffers contain volute, spiral, or india-rubber springs, and may be tested at 1, 2, and 3 inches compression with certain specified weights: the spindles should be fair and the plungers a good fit, otherwise sticking and non-return of the buffer head occurs.

TABLE LXII.—Showing Deflection of Springs Compressed under Varying Load.

Type.		Length between Centres.	Number and Thickness of Plates.	Camber Unloaded.	Deflection, per ton.											
					1.	2.	3.	4.	5.	6.	7.	8.	9.	10.		
Engine, . .	Bearing, . .	Ft. Ins. 2 10	Ft. Ins. In. 10 5 × ½	Ins. $2\frac{7}{8}$	In. $\frac{1}{8}$	In. $\frac{1}{8}$	In. $\frac{1}{8}$	In. $\frac{1}{8}$	In. $\frac{1}{8}$	In. $\frac{3}{16}$	In. $\frac{1}{8}$	In. $\frac{1}{8}$	In. $\frac{1}{8}$	In. $\frac{1}{8}$		
,, bogie,	,, . .	3 6	4 5 × $\frac{5}{8}$ / 8 5 × ½	$4\frac{7}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{3}{16}$	$\frac{3}{16}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{3}{16}$	$\frac{1}{8}$	$\frac{1}{8}$		
,, . .	,, . .	Timmis' spiral	6 ins. dia., / 2 ins. hole	$12\frac{5}{8}$ long	$\frac{1}{4}$	$\frac{5}{16}$	$\frac{5}{16}$	$\frac{5}{16}$	$\frac{5}{16}$	$\frac{1}{4}$	…	…	…	…		
,, . .	,, . .	Spiral	$6\frac{1}{2}$ ins., $2\frac{1}{8}$ ins.	$12\frac{7}{8}$,,	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{3}{16}$	$\frac{3}{16}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$	$\frac{1}{8}$		
					Deflection, per ½ ton.											
					5.	1.	1·5.	2.	2·5.	3.	3·5.	4.	4·5.	5.	5·5.	6.
Carriage, . .	Bogie bearing,	Ft. Ins. 5 0	Ft. Ins. In. 9 3½ × ½	Ins. 6	$\frac{3}{4}$	$\frac{5}{8}$	$\frac{5}{8}$	$\frac{5}{8}$	$\frac{11}{16}$	$\frac{5}{8}$	$\frac{11}{16}$	$\frac{5}{8}$	…	…	…	…
,, . .	Buffing, . .	5 8	2 3 × $\frac{7}{16}$ / 18 3 × $\frac{3}{8}$	15	$\frac{11}{16}$	$\frac{13}{16}$	$\frac{15}{16}$	$\frac{7}{8}$	$1\frac{5}{16}$	$1\frac{1}{8}$	1	$1\frac{1}{8}$	$1\frac{1}{8}$	$1\frac{1}{8}$	$1\frac{1}{8}$	$1\frac{1}{16}$
10-ton waggon,	Bearing, . .	3 9	9 4 × ½	6	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{3}{8}$	$\frac{1}{4}$	$\frac{1}{4}$	$\frac{3}{16}$
7-ton ,, .	,, . .	3 9	7 4 × ½	7	$\frac{3}{8}$	$\frac{5}{16}$	$\frac{3}{8}$	$\frac{5}{16}$	$\frac{5}{16}$	$\frac{3}{8}$	$\frac{5}{16}$	$\frac{3}{8}$	$\frac{5}{16}$	$\frac{3}{8}$	$\frac{5}{16}$	$\frac{5}{16}$
Waggon, . .	Buffing, . .	5 $11\frac{3}{4}$	1 3 × $\frac{7}{16}$ / 18 3 × $\frac{3}{8}$	$14\frac{1}{2}$	1	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{2}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	$1\frac{1}{4}$	…	…
Horse-box, .	Bearing, . .	4 0	7 4 × ½	$3\frac{1}{2}$	$\frac{11}{16}$	$\frac{11}{16}$	$\frac{3}{4}$	$\frac{11}{16}$	$\frac{11}{16}$	…	…	…	…	…	…	…

CHAPTER XV.

CARBON AND IRON.

The mutual relations of Carbon and Iron is a subject which, until comparatively recent years, had not been systematically investigated. While the peculiar characteristics possessed by steel have been recognised from the very earliest times, yet the explanation of the phenomena of hardening, tempering, and annealing, constituted problems the solution of which became possible only by the higher development of more exact processes of chemical analysis, and investigation involving the application of technical skill of a high order. It was not until 1781 that the chief cause of the phenomena referred to was shown by the Swedish chemist Bergman to be the presence in steel of varying, though small, amounts of Carbon.

Many and varied were the recipes of early writers for the treatment of steel, but all knowledge of the subject was empirical, the nature of the fluid employed for quenching being regarded as the secret to successful treatment. The constitution and behaviour of steel formed a wide field for the speculations of supporters of the doctrine of Phlogiston, and the eminent chemist Stahl, while recognising the essential identity of iron and steel, held the belief that the difference lay solely in the relative richness of the latter in Phlogiston. The developments of physical chemistry have led us to regard changes occurring in solid matter, such as steel, as due to molecular disturbances.

These modern views were foreshadowed in a remarkable manner by Reaumur, who regarded steel as containing in its molecules Sulphurs and Salts which by heating were driven out from the molecules into the interstitial spaces, and that by sudden cooling the particular conditions existing at any temperature were preserved. Bergman, to whom reference has already been made as having established the fact that steel differs from iron in containing small amounts of Carbon, also conceived the possibility of the iron itself being allotropic at different temperatures. Although anticipating in a remarkable manner the views of modern workers, as will be shown later, Bergman seems to have been influenced, in common with other writers of this period, by the necessity of adhering to the conception of Phlogiston.

The Direct Combination of Iron and Carbon.—The verification of Bergman's statement with respect to iron and Carbon quickly followed when Clouet, as pointed out by Sir W. Roberts-Austen, melted a small iron crucible containing a diamond and obtained as the result a fused mass of steel. The question of the possible effect of furnace gases was eliminated by Pepys, who, in 1815, heated iron wire with diamond dust *in vacuo*, while later Clouet's experiment has been repeated by Sir W. Roberts-Austen, who used electrolytic iron and performed the operation *in vacuo*. As to the possibility of direct carburisation of the iron there can be no doubt, but it would seem, as the result of this experiment, that combination does not take place until a full red heat is reached. This disposes of the assumption made by Le Play and early writers that the cementation of iron necessarily involves the action of Carbonic Oxide, and shows that Carbon may diffuse into and combine directly with iron.

Limits to the Amount of Carbon taken up by Iron.—In the molten state, *pure* iron is capable of dissolving up to about 7 per cent. of Carbon, but on solidification only 2 per cent. is held in solution, and in alloys containing more than 2 per cent. the excess over this separates on solidification. The total amount of Carbon, however, retained on soldification depends in a great measure on the purity of the alloy; and the presence in any considerable quantity of other elements, such as Manganese, may greatly increase the amount of Carbon retained.

Condition of Carbon in Iron.—The earliest evidence as to the condition in which Carbon exists in iron was that adduced by Faraday, who, in 1822, established the fact that at least two different conditions existed in quenched and annealed steel respectively, the former dissolving completely in dilute Hydrochloric Acid while the latter left a carbonaceous residue. Caron* worked on similar lines, and showed that rolled steel gave a larger amount of carbonaceous residue than hammered, and stated that the amount obtainable was proportional to the time of annealing. Rinman, in 1865, proposed to assign names to the two forms of Carbon existing respectively in quenched and worked steel, and in blister and unworked (annealed) steel. To the first he gave the name "hardening" Carbon, and to the second "cement" Carbon. Karsten also recognised these forms, and also Graphite. He regarded cement Carbon as a Polycarbide of Iron. This idea of the existence of Carbides of Iron has long prevailed in the minds of chemists. Berthier was of the opinion that a Carbide, FeC, existed, while Berzelius believed in the existence of Carbides FeC_2 and Fe_2C_3.

Karsten, moreover, supposed the condition of the Carbon in hardened steel to be identical with the Polycarbides of white iron. The existence of a definite Carbide of Iron in annealed steel and white iron was first established by Abel, who, by means of Chromic Acid solutions, isolated a Carbide of the general composition Fe_3C.

Müller obtained a residue from Bessemer steel which was pyrophoric. Following this came work on the thermal effects produced by dissolving in acid, steels differently treated, with a view to determining whether this would throw any light on the Carbon condition. In annealed and hardened steels it was shown that the higher the Carbon percentage the less was the amount of heat evolved on solution, and hence it is to be supposed that the separation of the Carbon from the iron results in an absorption of heat.

In the hardened state more heat is evolved than in the annealed condition, but in considering the Carbon in steel which has been cold-worked, difficulties arise. Abel has shown that cold-working does not produce hardening Carbon, although the amount of heat evolved is nearly as great as in case of quenched steels; in the case of cold forged steel the heat evolved is the same for steels containing ·17 or ·54 per cent. of Carbon, which seems to show that no relation exists between the total percentage of Carbon and the heat evolved.

It is possible that Carbon may exist in steel in various forms and combinations, but Graphitic Carbon, Cement Carbon, and Hardening Carbon are accepted by all metallurgists.

Graphitic Carbon.—This is comparatively rarely found in steels, and then in small quantities only, and is confined almost entirely to cast iron. When molten iron has taken up more carbon than the solidified metal is able to retain, the excess is found as Graphite on the metal solidifying. It is attacked neither by boiling Hydrochloric nor by Nitric Acid (sp. gr. 1·20).

*Percy's *Metallurgy*.

Cement Carbon.—This is the Fe_3C first isolated by Abel, by dissolving steel in a Sulphuric Acid solution of Bichromate of Potash.* It has long been recognised as existing in *unhardened steels*, and as being left insoluble on dissolving the steel in certain dilute acids. This is the same as the cement Carbon of Rinman, although it was left for Abel to prove that it was a definite Carbide.

With weak Hydrochloric or Sulphuric Acid, the Carbide remains in the form of a grey-black powder. On heating in Nitric Acid of 1·18 to 1·2 specific gravity, this form of Carbon dissolves, imparting a brown colour to the iron solution—a reaction used in the well-known Eggertz colour-test for the determination of Carbon. According to Osmond, this Carbide forms during the slow cooling of highly-heated carboniferous iron, at a temperature between 660° and 708° C., its formation being accompanied by an evolution of heat.

Arnold and Read† have separated this Carbide by an electrolytic method.

Hardening Carbon.—This form of Carbon escapes as a Hydrocarbon with an unpleasant smell, even at the ordinary temperature, if the iron is dissolved in dilute Sulphuric or Hydrochloric Acid. When dissolved in cold Nitric Acid, the hardening Carbon remains as a black residue, which, on gentle heating, rapidly dissolves, and, on stronger heating—to 100° C.—escapes as a gas, as was originally shown by Osmond and Werth. This hardening Carbon is almost completely soluble in the chromic solvent of Abel. It is found in quenched steels, and the hardness, brittleness, and tenacity of the steel increase with the percentage of this hardening Carbon, but diminish again when the percentage passes a certain limit. The more rapid the cooling of the steel the larger is the percentage of hardening Carbon found, but, according to Ledebur,‡ on reheating the steel to as low a temperature as 200° C., the iron Carbon alloy commences to slightly decompose with the formation of Fe_3C and iron, and the higher the temperature is raised the more marked does this transformation become.

Temper Carbon. — Professor Ledebur recognises another modification of Carbon, which he has called temper Carbon, describing it as greatly resembling, but distinct from, Graphite. It takes its name from the fact that it is mainly formed during the prolonged heating of white pig iron during the tempering or annealing process. In steel that contains upward of 1 per cent. of Carbon, and has been heated to redness, this form of Carbon may be observed. When the iron is dissolved in acids, the temper Carbon behaves exactly like Graphite—that is to say, it is not attacked by boiling Hydrochloric or Nitric Acid. The temper Carbon differs, however, from Graphite by its amorphous condition, and still more in that when the iron is heated under oxidising conditions (for instance, in contact with iron ore, as in the manufacture of malleable castings), it somewhat rapidly disappears, even when it occurs, not on the surface, but in the interior, of the iron mass, whilst Graphite remains unaffected by this treatment. The existence, however, of this form of Carbon has not been confirmed by other investigators, and the general opinion appears to be that it is really modified Graphite with special physical properties.

Professor Arnold has, in conjunction with Mr. Read, very carefully studied the question of the mode of combination of Carbon in steel. The

* *Iron*, 1883, vol. i., p. 76; and 1885, vol. i., p. 115.
† *Journal Chem. Soc.*, Aug., 1894.
‡ *Iron and Steel Inst. Journ.*, 1893, vol. ii., p. 60.

following are the results they arrived at, as detailed in a paper read before the Chemical Society*:—

(1) "That the existence of a Carbide of iron possessing the formula Fe_3C, as discovered by Abel and Müller by independent methods, is fully confirmed."

(2) "That the normal Carbide exists in two forms identical in chemical composition—(*a*) a diffused Carbide scattered in microscopic granules, or very small plates, throughout the iron in normal steel, yielding, on isolation, a greyish-black powder; (*b*) a crystalline Carbide arranged in comparatively large distinct plates in well-annealed steel: these plates, which occur chiefly in the form of well-marked striæ, consist of almost chemically pure Fe_3C, are identical with the microscopical laminæ of Dr. Sorby's 'pearly constituent,' and yield, when isolated, bright silver plates."

(3) "That the percentage of the total Carbon obtained as Carbide is greater in hard than in mild steel, the yield being, in normal numbers, as follows:—

For iron containing	1·00	per cent. C,	92	per cent.; loss,	8	per cent.
"	"	0·50	"	87	"	"	13	"
"	"	0·25	"	74	"	"	26	" ."

(4) "That the above loss does not appear to be due to decomposition, but rather to the presence of an unstable sub-Carbide of iron (containing less Carbon than the normal compound), existing to the extent of about 25 per cent. of the total Carbon in mild steel, and capable also of existing to the same extent in hard steel, after the latter has been heated for some time at a white heat."

(5) "That the loss being practically the same in well-annealed steel as in the normal metal, it cannot be due, as supposed by Ledebur, to the presence of hardening Carbon."

(6) "That the Carbon in hardened steel exists as a feebly combined and extremely attenuated Carbide, leaving, on isolation, a residue consisting mainly of Hydrate of Carbon, mixed to a slight extent with normal Carbide of iron. Whether the large loss of Carbon (about 50 per cent. of the total) occurring during the galvanic decomposition of hardened steel is due to the presence of a large percentage of sub-Carbide, or to evolved Hydrocarbons formed by the action of nascent Hydrogen on finely-divided, free, or feebly combined Carbon, there is no conclusive evidence to show, although the evolution of gas from hardened steel does not perceptibly exceed that from unhardened samples."

(7) "That in steel high in Manganese a portion of the iron may be replaced by Manganese, and that the double Carbide is less stable than that of iron alone, especially in normal steels."

In a paper read before the Iron and Steel Institute by Messrs. E. D. Campbell and M. B. Kennedy† some interesting results are given on the separation of Carbides from annealed white iron. From very pure white iron which had been subjected to long annealing the authors obtained, on dissolving the iron by electrolysis, a Carbide residue which could be separated by mechanical sifting into a coarse and a fine portion. The former contained less Carbon than the latter, and although varying somewhat in analysis approximated to the formula, Fe_3C, while the latter gave results corresponding nearly to the formula, Fe_2C. The chemical behaviour of the two Carbides was almost identical, but Fe_2C seemed to be less soluble in Potassium Cupric Chloride and Hydrochloric Acid than the Fe_3C, although not to a marked extent. The authors are of opinion

* *Journal of the Chemical Society*, vol. lxv., p. 788, 1894.
† *Iron and Steel Inst. Journ.*, 1902, vol. ii.

that they have isolated two Carbides, Fe_2C and Fe_3C, but that the molecular formula is some multiple of these, and may be expressed by the general formulæ, $(Fe_2C)_n$ and $(Fe_3C)_n$.

Although the different conditions under which Carbon exists in steel are still disputed points, the effects of different percentages of Carbon on the physical properties of steel, and the influence they exert, either directly or indirectly, when the steel is subjected to different heat treatment, have now been fairly well demonstrated. Whether these physical changes are due to the Carbon *per se*, or whether they are due to some allotropic change in the iron itself, induced by the presence of Carbon, does not concern us at the present moment, as the facts are the same whatever the cause, and it is these alone we have now to consider.

Influence on Physical Properties.—When a bar of steel containing less than about ·15 per cent. of Carbon is quenched in water from a full red heat there is no very appreciable hardening of the bar, as shown by an ordinary bend test,* but in the case of steels containing over ·2 per cent. of Carbon, the hardening by rapid cooling at once becomes apparent, and increases with the percentage of Carbon present, at all events up to about 1 per cent. This is so well known that it has always been customary since the manufacture of steel became an established industry, to grade the steels according to their Carbon content, and we are thus enabled to select steels of varying degrees of hardness for different purposes, such as chisels, dies, saws, springs, files, razors, &c. The degree of hardness conferred on any grade of steel will vary with the temperature from which the steel is quenched or cooled and the rapidity of quenching, and by varying these, very different results may be obtained. Thus, if the highest degree of hardness is required for a medium Carbon steel, it is obtained by quenching from a full red heat in mercury or iced brine, while quenching in hot water, oil, or molten lead would have a much less hardening effect. For most purposes the hardness induced by rapid cooling in water or oil is too great, as with the hardness the brittleness of the material increases, and it is necessary to modify this by reheating to certain definite temperatures. This is called tempering, and may be regarded as regulating or modifying the hardness conferred by quenching, to suit the purpose required; it is known in practice as "letting down" the steel. It reduces the brittleness and increases the toughness and elasticity of the material, and by thus reheating hardened steel to different temperatures, different degrees of hardness may be obtained. When a bar of bright steel is gradually heated in air, series of colours appear successively on the surface, first a light straw colour, then dark straw, gold, brown, purple, light blue, deep blue, and finally black. These colours are oxidation films, and indicate very accurately successive changes in the temperature of the steel, and enable the practical man to reduce or regulate the hardness of a quenched steel by stopping the heating at any required point. The particular point to which the heating should be carried depends upon the purpose for which the steel is required, different tools requiring different degrees of tempering. The following table for tempering is given by Metcalf† :—

Light straw to straw, . . .	For lathe tools, files, &c.
Light brown (gold) to dark brown, .	,, taps, reamers, drills, &c.
Pigeon-wing (purple), . . .	,, axes, hatchets, and drills.
Light blue, ...	,, springs.
Dark blue, ...	,, some springs (seldom used).

* The hardening of carbonless steel is referred to on p. 358.

† *Manual for Steel Users*, p. 117.

These particular colours for the given purposes are simply those which have been arrived at as the result of experience, and have been found broadly to give the best practical results; but different workmen will vary the "tempering" to suit their special conditions. The word temper, when used as a verb, always means this modifying of the hardness, but as a noun it is frequently used in a different sense, to indicate the grade of the steel. Thus when a steel is spoken of as high, low, or medium temper, it does not mean that it has been tempered at a high, low, or medium temperature, or that it is of a certain degree of hardness, but that it is a high, low, or medium Carbon steel, and is a steel *capable* of taking a high, low, or medium degree of hardness in quenching. Thus 1·5 Carbon steel would be spoken of as high temper, and ·3 Carbon as low temper. On the other hand, when a steel is said to have taken a certain "temper," it means that it is hardened to a definite extent. It is important to bear these distinctive meanings in mind, as, otherwise, they are liable to lead to confusion.

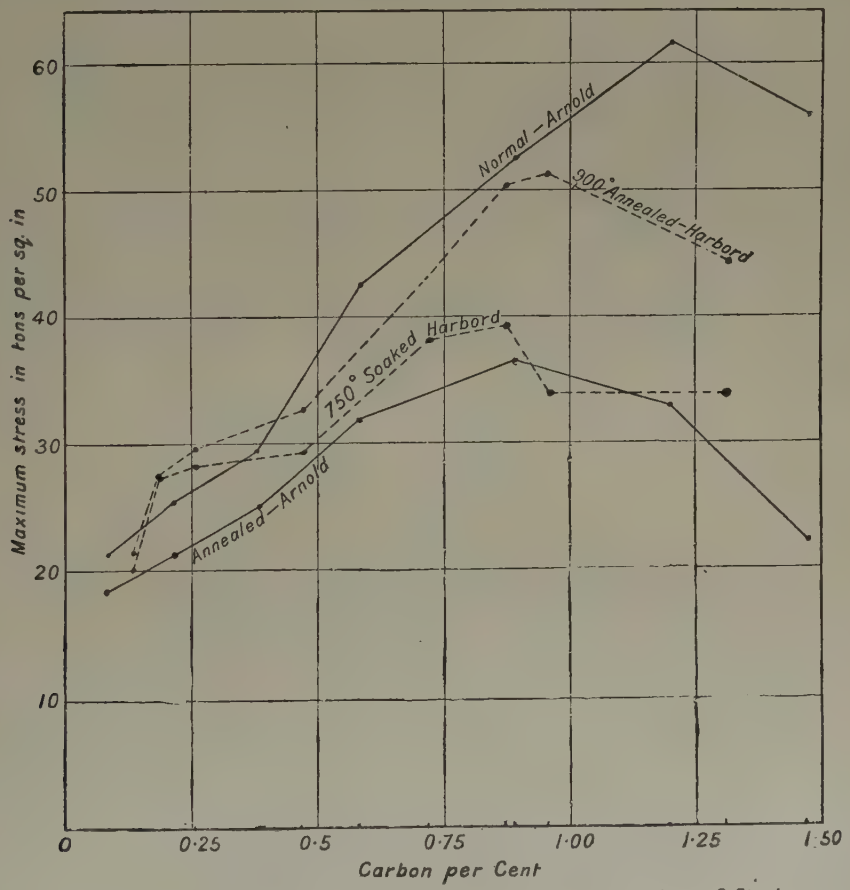
In hardening and tempering, the steel to be operated upon should be carefully and uniformly heated to a red heat (about 850° C.), and quenched in water. The surface is then filed bright, and carefully and gradually heated on a hot iron plate, the surface of molten lead, a fusible alloy, or in any other convenient way, until the surface coloration indicates that the required temperature has been reached, when the material must be removed immediately and either immersed in water or oil, or allowed to cool in the air. In many cases where the whole of the metal is required of the same degree of hardness air cooling is quite satisfactory, but in cases where only the cutting part of a tool requires tempering it is not unusual to quench the cutting edge and temper it by the heat conducted from the unquenched end: in this case, directly the cutting edge shows the required colour, the whole tool must be quenched, as otherwise the heat from the hot end will continue to flow and will make the cutting edge too soft. It is this property which Carbon steel possesses of hardening and tempering which distinguishes it from wrought iron and from very mild steel.

Influence on Tensile Strength.—The influence of different percentages of Carbon on the tensile strength and other physical properties of steel, is a question which has been the subject of investigation by various metallurgists. In 1895 Professor Arnold* gave the results of a very complete research on a set of extremely pure steels varying from ·08 per cent. Carbon to 1·47. The author has lately repeated these experiments on a similar set of pure steels under somewhat different conditions as to heat treatment, and, so far as the general mechanical effects are concerned, has confirmed Arnold's results. Below are given the analyses of both sets of steels with the tensile tests, and for comparison the tenacity and elongation curves are shown diagrametrically together on the two diagrams (figs. 248 and 249). It will be seen that the general character of the tenacity curves is very similar, the maximum stress in the case of the author's bars being reached at a somewhat lower point, about 1 per cent. Carbon, as against 1·2 in the Arnold curve. This is accounted for, however, by the somewhat slower cooling to which the former annealed bars were subjected. In considering these curves the author's bars, annealed at 900° C. for thirty minutes and slowly cooled, must be compared with Professor Arnold's normal bars heated to 1,000° and cooled in air; and the author's soaked bars, heated for twelve hours and slowly cooled, with Professor Arnold's annealed bars, heated for seventy-two hours at 1,000° C. and slowly cooled. Professor Arnold's

* "Influence of Carbon on Iron," *Min. Proc. Inst. Civil Engineers*, vol. cxxiii., 1895-96.

normalising conditions correspond nearly to the author's annealing, and his annealing to the author's twelve-hour heating. The elongation curves are very similar in general character, the variations being such as might be expected from the difference in the temperature, time of heating, and composition of the steels.

We may therefore take it as established that the tensile strength of pure Carbon steels will vary from about 19 tons in case of ·08 Carbon steel to about 53 tons with 1 per cent. Carbon, and above this point the tenacity will vary somewhat till 1·2 per cent. Carbon is reached, in some cases giving as much as 61 tons and in others less than 50 tons per square inch, according to the temperature to which they have been heated. This applies



Curves showing the influence of Carbon on tenacity of Steels

Fig. 248.

Arnold-normal	= heated	1,000° C.	cooled in air.
,, -annealed	= ,,	1,000° C. (72 hours)	cooled in furnace.
Harbord ,,	= ,,	900° C. (30 minutes)	,, ,,
,, -soaked	= ,,	750° C. (12 hours)	,, ,,

Arnold's normal bars comparable with Harbord's annealed bars, and Arnold's annealed bars with Harbord's soaked bars.

to steels that have been heated only sufficiently long to remove the stains due to mechanical work. The elongation gradually decreases as the Carbon increases from about 45 per cent. in ·08 Carbon steel to about 3 or 4 per cent. in case of 1·5 Carbon steel.

The effect of heating, broadly speaking, is to lower the tenacity and increase the ductility, but the results obtained vary with the heat treatment and this will be more fully dealt with in Chap. xviii. on Heat Treatment. In the curves of steels which have been subjected to prolonged heating, both in Professor Arnold and the author's results there is a very noticeable

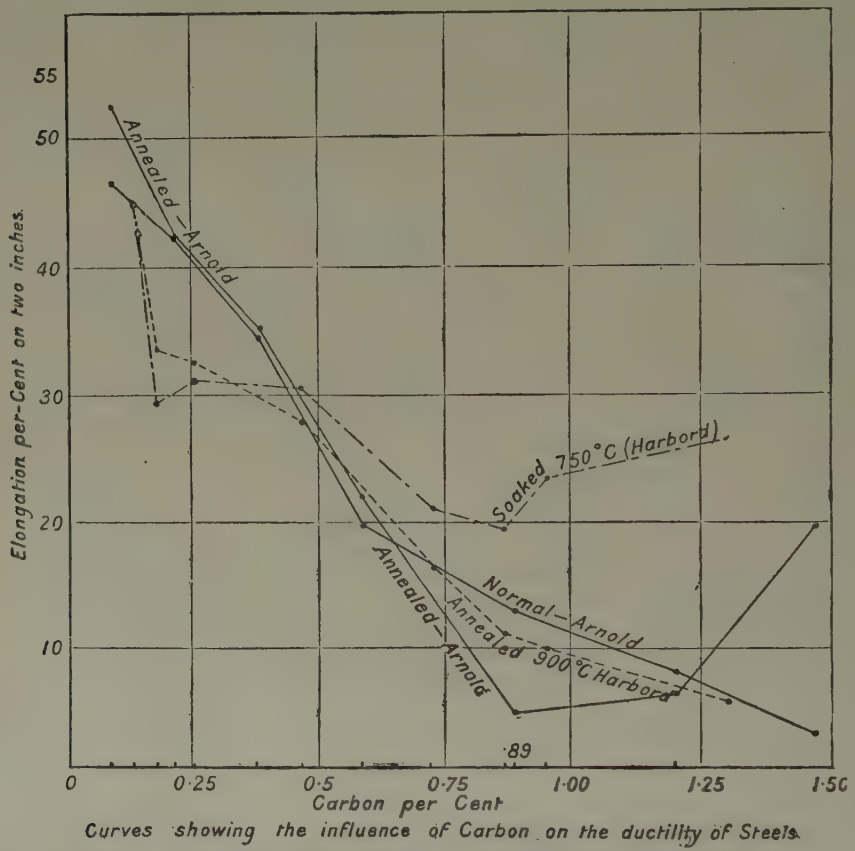


Fig. 249.—Normal Arnold curve comparable with annealed curve, Harbord and Arnold-annealed curve with soaked curve, Harbord.

point between ·87 and 1 per cent. of Carbon at which the maximum stress is attained.

In the elongation curve there is also a break, as up to this point the ductility has been gradually decreasing, when it suddenly begins very slightly to increase again, and goes on steadily increasing until 1·5 per cent. Carbon is reached. These changes in mechancial properties correspond to a very definite change in microscopical structure, as when steel

contains ·89 per cent. of Carbon it is found to consist entirely of Pearlite,* and this point has been called by Professor Arnold the saturation point. If the percentage of Carbon is increased the Micro-constituent, Cementite, separates out, and if the Carbon is decreased free Ferrite appears.

Professor Arnold's Results. Normal Bars.

TABLE LXIII.—Tensile Tests of Bars Heated to about 1,000° C. and allowed to Cool in Air.

Steel No.	Analyses.							Elastic Limit.		Maximum Stress.		Elongation per Cent.	Reduction of Area per Cent.	Fracture.
	Total Carbon.	Graphite in Annealed Sample.	Silicon.	Manganese.	Phosphorus.	Sulphur.	Aluminium.	Tons per Square Inch.	Lbs. per Square Inch.	Tons per Square Inch.	Lbs. per Square Inch.			
1*a*	0·08	...	0·03	0·02	0·02	0·03	0·02	12·19	27,300	21·39	47,920	46·6	74·8	Grey granular silky edges.
1½*a*	0·21	...	0·05	0·05	0 02	0·03	0·02	17·08	38,270	25·39	56,860	42·1	67·8	,, ,,
2*a*	0·38	...	0·03	0·08	0·02	0·02	0·03	17·95	40,200	29·94	67,080	34·5	56·3	,, ,,
3*a*	0·59	...	0·07	0·10	0·02	0·02	0·03	19·82	44,400	42·82	95,920	19·9	22·7	Crystalline.
4*b*	0·89	...	0·03	0·09	0·02	0·02	0·03	24·80	55,550	52·40	117,150	13·0	15·4	,,
5*b*	1·20	0·28	0·07	0·15	0·02	0·02	0·03	35·72	80,000	61·65	138,100	8·0	7·8	,,
6*b*	1·47	1·14	0·08	0·13	0·02	0 01	0·04	32·27	72,300	55·71	124,800	2·8	3·3	,,

a, Average of two tests. *b*, Average of three tests.

Author's Results. Annealed.

TABLE LXIV.—Heated to a Temperature of 900° for 30 Minutes and Allowed to Cool Slowly in Muffle.

Steel No.	Analyses.					Elastic Limit.		Maximum Stress.		Elongation per cent. on 2 Ins.	Reduction of Area per cent.	Remarks.
	Total Carbon.	Silicon.	Manganese.	Phosphorus.	Sulphur.	Tons per Sq. In.	Lbs. per Sq. In.	Tons per Sq. In.	Lbs. per Sq. In.			
1	0·130	0·020	0·185	0·011	0·020	13·02	29,100	21·48	48,100	45·00	71·16	Elastic limit for bars 5, 6, 7, and 8 was so doubtful that result not recorded.
2	0·180	0·024	0·250	0·022	0·020	15·84	35,500	27·84	62,350	33·50	60·24	
3	0·254	0·032	0·190	0·025	0·020	17·28	38,300	29·46	66,000	32·50	54·84	
4	0·468	0·072	0·160	0·016	0·025	18·03	40,400	32·46	72,700	28·00	46·26	
5	0·722	0·098	0·217	0·015	0·020	...	...	43·20	96,780	16·50	25·86	
6	0·871	0·080	0·190	0·019	0·019	...	...	50·40	112,900	11·20	15·84	
7	0·947	0·081	0·181	0·013	0·019	...	...	51·12	114,700	10·00	15·42	
8	1·306	0·050	0·180	0·015	0·017	...	...	44·52	99,760	5·50	5·58	Broke at gauge point; fracture finely crystalline.

* See Chap. xix. on the Microstructure of Steel.

Professor Arnold's Results. Annealed Bars.

TABLE LXV.—BARS HEATED TO ABOUT 1,000° C. FOR 72 HOURS AND ALLOWED TO COOL IN FURNACE FOR 100 HOURS.

Steel No.	Carbon per Cent.	Elastic Limit.		Maximum Stress.		Elongation per Cent.	Reduction of Area per Cent.	Fracture.
		Tons per Square Inch.	Lbs. per Square Inch.	Tons per Square Inch.	Lbs. per Square Inch.			
1	0·08	8·82	19,750	18·34	41,090	52·7	76·7	Grey granular silky edges.
1½	0·21	9·02	20,200	21·25	47,610	42·3	65·7	,, ,, ,, ,,
2	0·38	9·55	21,280	25·02	56,040	35·0	50·6	,, ,, ,, ,,
3	0·59	11·36	25,460	31·87	71,400	22·0	23·3	Crystalline.
4	0·89	16·81	37,650	36·69	82,180	4·5	4·2	,,
5	1·20	16·19	36,280	32·87	73,650	6·0	4·9	,,
6	1·47	10·08	24,200	22·33	50,000	19·0	17·7	Dark grey fibrous

Author's Results. Soaked Bars.

TABLE LXVI.—HEATED FOR TWELVE HOURS AT 725° C. AND ALLOWED TO COOL IN MUFFLE.

Treatment.	No.	Total Carbon.	Size Diam. Inch.	Elastic Limit.		Maximum Stress.		Elongation per cent. on 2 Ins.	Reduction of Area per cent.
				Tons per Sq. In.	Lbs. per Sq. In.	Tons per Sq. In.	Lbs. per Sq. In.		
Twelve hours soaking at a temperature of 720° C.	1	0·130	0·454	11·666	26,150	20·000	44,800	42·50	73·21
	2	0·180	0·451	7·625	17,080	27·750	62,170	29·50	61·11
	3	0·254	0·445	15·806	35,400	28·180	63,120	31·00	57·28
	4	0·468	0·450	11·761	26,350	29·308	65,800	30·50	42·70
	5	0·722	0·450	16·163	36,200	38·113	85,380	21·00	35·97
	6	0·871	0·455	15·276	34,200	39·386	88,200	19·50	29·69
	7	0·947	0·448	14·114	31,620	33·734	75,570	23·50	35·44
	8	1·306	0·452	11·687	26,170	33·375	74,750	26·50	34·50

The results of Professor Arnold's compression tests show that the flow of material decreases gradually, both in the normal and annealed bars, until the point ·89 per cent. of Carbon is reached, when, in the case of the former, there is a very slight decrease to 1·5 per cent. of Carbon, and in the case of the latter the compressibility goes on increasing until, with 1·5 per cent. of Carbon, it is greater than that of nearly Carbonless steel. In steel which has been hardened by rapid cooling in water from a high temperature, according to Arnold's results, ·89 per cent. Carbon again marks the point of least compression, there being practically no change between this and 1·5 per cent.

Metcalf* states that the compressibility of steel goes on decreasing as the Carbon increases until cast iron is reached, and other metallurgists take the same view, but how far these are founded upon systematic experiments with pure Carbon steels without the disturbing influence of other elements it is difficult to say.

The author is not able to give any results showing the variations in

* *Manual for Steel Users*, p. 46.

hardness of steel due to increasing percentages of Carbon in pure Carbon steels, but the results obtained by Wahlberg, using Brinell's hardness test on a set of steels containing somewhat varying percentages of Silicon and Manganese are given below.*

TABLE LXVII.—Influence of the Percentage of Carbon on the Hardening Capacity (Brinell's Results).

Materia No.	Chemical Composition.					Hardness Numbers.		Hardening Capacity.
	C.	Si.	Mn.	S.	P.	Annealed.	Quenched in Water + 20° C.	
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.			
1	0·10	0·007	0·10	0·020	0·026	97	149	1·54
2	0·20	0·018	0·41	0·015	0·027	115	196	1·70
3	0·25	0·30	0·41	0·012	0·028	143	311	2·18
4	0·35	0·26	0·49	0·015	0·027	156	402	2·58
5	0·45	0 27	0·45	0·018	0·028	194	555	2·86
6	0·65	0·27	0·49	0·011	0·028	235	652	2·77
6a	0·66	0·33	0·18	0·010	0·028	202	578	2·86
8	0·78	0·37	0·20	0·011	0·028	231	652	2·82
9	0·92	0·28	0·25	0·012	0·026	258	627	2·43
12	1·25	0·60	0·20	0·510	0·027	262	627	2·39

The influence of rapid cooling from high temperatures on steels containing over ·2 per cent. of Carbon is very marked, the tensile strength increases, and a most marked reduction of the ductility is found for every increment in Carbon, as shown by the decrease in elongation and reduction of area.

The following results were obtained on heating to 900° C. and quenching in water:—

TABLE LXVIII.—Heated to 900° C. and Quenched in Water at 15° C.

Steel No.	Analyses.	Elastic Limit.		Maximum Stress.		Elongation per cent. on 2 Inches.	Reduction of Area per cent.	Remarks.
	Total Carbon.	Tons per Sq. Inch.	Lbs. per Sq. Inch.	Tons per Sq. Inch.	Lbs. per Sq. Inch.			
1	0·130	24·30	54,500	32·34	72,480	28·20	76·26	It was not possible to get a reliable elastic limit for any bar below No. 1. General analyses given in table lvii.
2	0·180	...	...	49·92	111,850	6·50	35·28	
3	0·254	...	...	70·32	157,500	3·80	13 44	
4	0·468	...	...	†55·44	124,200	1·00	2 64	
5	0·722	...	...	61·98	138 840	1·00	2·56	
6	0·871	...	...	†26·04	58,320	2·00	2·16	
7	0·947	...	...	†21·60	48,400	nil	nil	

The mechanical properties vary with the initial temperature of heating and the rapidity of cooling. They may be regulated or modified by reheating or tempering to various temperatures.

Influence on Magnetic Properties.—It is well known that practically carbonless steel cannot be permanently magnetised, and that as

* *Iron and Steel Inst. Journ.*, No. 1, 1901, p. 267.

† The irregular results obtained with these samples were due largely to their having warped during the quenching, and the first result of applying the load was to straighten them, which in the case of Nos. 6 and 7 caused them to break off short.

the Carbon increases so the power of retaining magnetism increases, and that this power of retention is increased by hardening. Arnold, as the result of his experiments, found that the magnetic permeability varied inversely as the Carbon present, and that permanent magnetism in hardened steels was directly proportional to the Carbon present up to ·89 per cent., after which there is no change up to 1·5 per cent. Carbon. On heating the hardened steels for thirty minutes at 300° C. the permanent magnetism was reduced to about one-third in the case of ·2 Carbon steel, and remained practically constant until ·89 per cent. of Carbon was reached. After passing this point there was a further reduction of nearly 50 per cent.

It must be borne in mind that all the above results as to the magnetic and general physical properties of Carbon steels refer only to steels of the highest degree of purity, containing practically nothing but Carbon and a little Manganese, and that these results are largely modified by the presence of very small quantities of Silicon, Sulphur, Phosphorus, or additional Manganese, or by any variation in the heat treatment. Professor H. M. Howe* has shown how variable these results are by tabulating a large series of results obtained by different investigators, and how difficult, if not impossible, it is to draw any definite conclusion as to the effect of Carbon on tensile strength and other properties of commercial steels, unless fullest details as to composition and treatment are known, and especially is this so in the case of the low Carbon steels up to 0·3 per cent. of Carbon.

Constitution of Steel.—Before considering the various theories which have been advanced to explain the changes induced in steel by heat treatment, and by sudden cooling or quenching, it will be necessary to describe the remarkable phenomena observed during the heating or cooling of steel, as they bear a most important relation to some of the theories advanced.

On heating up a specimen of steel and then allowing the sample to slowly cool, it is found during the cooling that there are certain points at which the cooling seems to stop or be arrested for a time, instead of proceeding normally. These points are known as the critical points, and, thanks to M. Osmond's researches, aided by the wonderfully accurate pyrometer, which we owe to the genius of M. Le Chatelier, we have now a complete record of them for all sorts of steel, ranging from the softest electrolytic iron to the hardest steel. On heating up the sample there are, of course, the reverse phenomena to those observed during cooling—that is, at certain points there is an absorption of heat, causing a retardation in the rise of temperature. The points at which such retardations during heating up take place correspond exactly with those obtained on cooling under theoretical conditions of equilibrium, but under ordinary conditions of heating and cooling are generally found to be some 20° to 40° higher than the latter. The points observed during heating up are designated Ac, whilst those observed during cooling are known as Ar. It has been shown by Professor Howe that, in order to induce the retardation Ar—or, rather, the change that such retardation implies—the steel must first be heated past the point Ac; and, reciprocally, the change which occurs at Ac cannot take place unless the steel has first been cooled to a point below Ar. It is found that in the softest varieties of steel, and in almost carbonless iron, there are at least three well-recognised critical points, the Ar_1 point, however, being almost imperceptible.

In medium steels the points Ar_3 and Ar_2 are combined in a single point,

* *Metallurgy of Steel*, p. 13, *et seq.*

and the Ar_1 point becomes much stronger. In saturated steels containing ·89 per cent. Carbon there is only a single point corresponding with Ar_1, and in steels containing more than ·89 per cent. Carbon two points are again observable, one corresponding to Ar_1 and a higher one, Ar_{mc}, corresponding to the separation of massive cementite.

The following give the approximate temperatures at which the maximum evolution of heat takes place during the cooling of steels of varying Carbon content through the critical ranges :—

	Ar_{mc}.	Ar_3.	Ar_2.	Ar_1.
Pure iron, ...	..	900	762	..
0·12 per cent. C., . . .	..	850	762	690
0·24 per cent. C., . . .	..	820	762	690
0·53 per cent. C., . . .	...	730		690
0·89 per cent. C., . . .	..		690	
1·31 per cent. C., . . .	883		690	

The point Ar_1 is nil in the case of carbonless iron, but increases in importance as the Carbon in the sample increases, being practically the only point observable in hard steel. It is, therefore, clearly a function of the Carbon present, and it is found that above the point Ar_1 the Carbon is in the state of hardening Carbon, whilst below this point it is in the state of cement Carbon, or Carbon which is combined with iron in the form of the definite Carbide, Fe_3C. The true state of the hardening Carbon is not known. It is probably Carbon either in the free state or as Carbide dissolved in the iron.

In regard to the critical points, it has also been shown by M. Osmond that the slower the heating the lower the temperature at which the transformation takes place, and that the slower the cooling the higher the temperature of the reverse transformation.

Professor H. Le Chatelier has summed up the chief characteristics of the points Ar_2 and Ar_3 thus:—The point Ar_2 is now known to be almost identical with the disappearance of magnetism in iron; it is accompanied by a slight absorption of heat, and its position varies little, being little affected by the rate of cooling or of heating. It occurs, moreover, nearly at the same temperature during heating and cooling. The point Ar_3 is characterised by a sudden change in the law of variations of the electric resistance, which is then ten times greater than at ordinary temperatures, but which practically ceases to increase above this critical temperature. This phenomenon, like that of recalescence, is affected by the rate of cooling or of heating.

The consideration of the above, and other recent experimental work, has led many of our leading metallurgists to form the conclusion that iron exists in different allotropic forms under different conditions of temperature, mechanical treatment, and purity.

Thus, modern views as to the constitution of steel involve two distinct phases for consideration: that which has for its object the study of the relations of Carbon and the elements to iron, and that concerned with the molecular changes occurring in the iron itself.

Allotropy.—The molecular changes occurring in iron itself have been very carefully studied, and form the basis of what is known as the allotropic theory. Sir Wm. Roberts-Austen defined allotropy as "a change of internal energy occurring in an element at a critical temperature, not necessarily accompanied by a change of state." Professor H. M. Howe has proposed the following definition:—"Allotropy is a change in the properties of an element without change of state. It is habitually accom-

panied by a change of internal energy. It is due in some, perhaps in all, cases to a change in the number or in the arrangements of the atoms in the molecule."* Taking either of the above definitions, it is clear that the evolution of heat on cooling, and the absorption of heat on heating, taken in conjunction with the altered physical properties of hardened steel, would be undoubted evidence of allotropy, once granting that Carbon or some other element plays no part in the observed phenomena; and, in the case of electrolytic iron (such as that used in some of Sir Wm. Roberts-Austen's experiments, with only 0·007 per cent. Carbon), the presence of the critical points Ar_3 and Ar_2 is undoubted evidence of allotropy, but not, of course, of itself, of a *hard* allotropic form.

In 1890, at the spring meeting of the Iron and Steel Institute, M. Osmond read a very notable paper in which he brought forward the theory that there are two allotropic modifications of iron, one the ordinary soft iron as we know it in ingot iron or steel, which he called "alpha" iron, and the other a hard variety as we know it in hardened steel, which he called "beta" iron.

Hardened steel, he asserted, owed its properties principally to the presence of β iron, which is hard and brittle by itself at the ordinary temperature. According to him, iron below the point Ar_2 possesses the molecular form "alpha"—that is, the soft form—but above the critical point Ar_2 the allotropic hard form, or "beta," iron exists. Between the points Ar_2 and Ar_3, when these two points are distinct, the metal is a mixture of the two varieties α and β. Carbon, in the state of hardening Carbon, maintains iron in the β condition, during slow cooling, to a temperature which is in inverse proportion to the amount of Carbon contained in the metal. When the rate of cooling is fairly rapid, the changes occurring during slow cooling do not take place, at least not in their entirety. Hardened steel is a steel in which the iron and Carbon have more or less completely preserved in the cold the condition which they possessed at high temperatures. It should be carefully noted that M. Osmond does not assume that hard "beta" iron is of itself sufficient to account for all the observed facts; Carbon undoubtedly plays an important rôle. On the other hand, although the presence of Carbon is essential to the hardening of steel, the changes of the Carbon do not enable all the facts to be explained. The influence of Carbon, according to him, is of the same character as that of the rate of cooling, and both combine to produce the final result. The rate of cooling alone is not sufficient, under the ordinary conditions in which hardening is effected, to maintain an appreciable fraction of the iron in the β condition. But as, under the same conditions, it is easy to maintain the Carbon in the state of hardening Carbon, and as the hardening Carbon imparts stability to β iron, β iron may be successfully preserved at the ordinary temperature by the aid of Carbon.

M. Osmond has, since 1890, recognised the existence of three distinct modifications of iron, his reasons being based chiefly on the distinction between the points Ar_2 and Ar_3, which in his early paper he did not think were independent and definitely separated. His latter view is that iron is in the α state below Ar_2, in the β state between Ar_2 and Ar_3, and in the γ state above Ar_3.

Sauveur† has shown that each critical point is accompanied by a marked change in the microstructure of the metal which begins and ends with it, and that such structural changes occur only within the range of

* "Nomenclature of Metallography," *Iron and Steel Inst. Journ.*, 1902, vol. i.

† Sauveur, "Microstructure of Steel," *Amer. Inst. Mining Engineers*, 1896.

temperatures of the critical points, and where there is no critical point no change is found in the microstructure of the steel.

The Carbon and Sub-Carbide Theories.—The allotropic theory has been strongly opposed by Professor Arnold and others. The supporters of the Carbon theories, as opposed to the allotropic theory, maintain that all the phenomena observed in the hardening of steel are explained by changes in the condition of the Carbon, and that hardening is not in any way due to allotropic modifications of the iron.

What may be termed the Carbon theory assumes that Carbon can exist in two states in steel; that the Carbon exists as "hardening Carbon" at a temperature above the critical points, and on rapid cooling, as by quenching in water, this Carbon is retained in the same state. On slow cooling from above the critical points, the hardening Carbon passes into the form known as cement Carbon, and combines with the iron to form the Carbide, Fe_3C. Even if this theory is accepted as a satisfactory explanation of hardening, it certainly does not explain the critical points in carbonless iron and other observed facts, such as the disappearance of magnetism at Ar_2. In May, 1894, Prof. Arnold* thus accounted for the critical points in steel:—Ar_1 is due to the combination of iron and Carbon to form the normal Carbide, Fe_3C; its intensity is proportional to the amount of Fe_3C present, and to the area of pearlite in the microsection. Ar_2 marks the exceedingly faint evolution or absorption of heat due respectively to the passage of iron from a plastic to a crystalline condition or *vice versâ*. Ar_3 is explained on the hypothesis that it marks the formation of a sub-Carbide of iron. In the case of low Carbon steels, a prolonged exposure to a white heat converts the normal into the sub-Carbide.

In 1896 Prof. Arnold† developed his sub-Carbide theory in an able paper, which may be thus briefly summarised:—

From a series of strictly comparative experiments on normal (heated to 1,000° C. and cooled in air), annealed, and hardened bars, he finds that in all the *hardened* steels only a small proportion, about 5 per cent., of the total Carbon is obtained on analysis as Fe_3C, the main portion, he argues, existing as an unstable sub-Carbide of iron. With steels of ·89 per cent. Carbon, it would appear from the analyses that, practically, the whole of the metal consists of this intensely hard sub-Carbide of iron. Steel of this percentage of Carbon he calls saturated steel; steels with other percentages are either unsaturated or super-saturated. The critical point Ar_1 is due to the dissociation of this Carbide, $Fe_{24}C$, and the formation of Fe_3C. In the *normal* samples some 90 per cent. of the total Carbon is obtained in the form of the definite Carbide, Fe_3C. He sums up thus:—

"The constituents of steel may be:—(*a*) Crystals of pure iron which remain bright on etching. (*b*) Crystals of slightly impure iron which become pale brown on etching, probably owing to the presence of a small quantity of unsegregated Carbide. (*c*) Normal Carbide of iron, Fe_3C, which exists in four distinct modifications, each one conferring upon the iron in which it is found particular mechanical properties:—(1) Emulsified Carbide present in an excessively fine state of division in tempered steels. (2) Diffused Carbide of iron occurring in normal steels in the forms of small ill-defined striæ and granules. (3) Crystallised Carbide of iron occurring as well-defined laminæ in annealed and in some normal steels. (4) Segregated Carbide occurring in very slowly-cooled steels, and consisting of irregular masses. (*d*) Sub-Carbide of iron, a compound of great hardness existing in hardened and tempered steels, and possessing the formula $Fe_{24}C$. This substance is decomposed by the most dilute acids, and at 400° C. it is

* *Iron and Steel Inst. Journ.*, 1894, vol. i. † *Min. Proc. Inst. C.E.*, vol. cxxiii., 1896.

decomposed into Fe_3C and free iron, with evolution of heat. One of the most remarkable properties of this compound is its capacity for permanent magnetism. (*e*) Graphite or 'temper Carbon.'

"The existence of $Fe_{21}C$ is proved by the fact that iron containing 0·89 per cent. Carbon presents several correlative critical points when examined by different methods of observation:—(1) Well-marked saturation points in the microstructure of normal and annealed steels. (2) A sharp maximum in a curve the co-ordinates of which are heat evolved or absorbed at Ar_1, and Carbon percentage. (3) A sharp maximum in a curve the co-ordinates of which are Carbon percentage, and permanent magnetism in hardened steels."

Prof. Arnold has kindly sent me the following paragraph briefly embodying his present views:—

"Since reading the paper in 1896, he has seen no reason to appreciably modify his views with reference to the critical point Ar_1, but considers, as Ar_2 is undoubtedly the magnetic change point, it does mark a kind of physical allotropy. With regard to Ar_3, the fact that this point has been shown by himself and others to be present in carbonless electrolytic iron precludes its being due to any Carbon change; it is also associated with dilatation phenomena, but he does not consider that this is necessarily evidence of an allotropic change, and, in the present state of our knowledge, has no satisfactory explanation to suggest except that it seems certain that neither Ar_2 nor Ar_3 is associated with crystalline polymorphism, and careful quenching experiments had proved that neither had any practical mechanical significance at ordinary temperatures. It is also certain that the view held by most well-known steel investigators (specifically excepting, of course, Prof. Le Chatelier) that Carbide of iron is insoluble in iron in the alpha range of temperature is curiously inaccurate. He (Prof. Arnold) had himself proved by scores of experiments that the Carbide of Pearlite completely diffused or dissolved into its iron in the alpha range."

In the autumn of 1895 Professor H. M. Howe presented a paper to the Iron and Steel Institute, the object of which was to investigate how closely the change in the Carbon condition, in passing through the critical range, coincides with the loss of the hardening power. Bars containing ·21 per cent. Carbon, ·31 per cent. Silicon, and 1·19 per cent. Manganese, were very carefully heated to 970° C., slowly cooled, and quenched at different temperatures, varying from 880° C. to 263° C. in cold brine, untreated bars being tested for comparison. These bars were then tested for tenacity, ductility, and hardness as a measure of the intensity of hardening, and for colour Carbon as a measure of the Carbon condition.

Professor Howe found that the change in Carbon condition (from cement to hardening Carbon) lagged far behind the change in tenacity. As the temperature of quenching descended from 880° to 713° the changes in the properties of the metal and the missing Carbon were slight, but at 633° the tenacity of the metal fell off most abruptly, at least 52 per cent. of the total loss occurring in this narrow range of 55°, though only some 12 per cent. of the Carbon change occurs here. Between 620° and 600° the Carbon changes very abruptly, with a very considerable increase in elongation, the recovery of the ductility, as measured by the elongation, seeming to be unduly concentrated into the latter part of the change in Carbon condition. Sauveur* made a very complete microscopic examination of the above steels, and his results in relation to the recalescent points are briefly these:—(1) Above Ar_2 no marked change occurred. (2) The upper part of Ar_2 showed a great change of Martensite to Ferrite, and no

* *Iron and Steel Inst. Journ.*, 1896, vol. i., p. 170.

TABLE LXIX.

	Carbon Theory.	Allotropic Theory.	Carbo-Allotropic Theory.	Prof. Arnold's Sub-Carbide Theory.		Microscopical Evidence.
Conditions of Carbon and iron above Ar_3.	Iron and hardening Carbon.	Carbon diffused in γ iron.		Carbon and iron combined as $Fe_{24}C$.	?	Very mild steel made up of Martensite and Ferrite.
Cause of the evolution of heat at Ar_3.	?	Passage of iron from γ to β state.		?	?	Separation of a certain amount of Ferrite previously included in Martensite.
Conditions of Carbon and iron between Ar_3 and Ar_2.	Iron and hardening Carbon.	Carbon diffused in β iron.		?	Carbon and iron combined as $Fe_{24}C$.	Soft and medium hard steel, made up of Martensite and Ferrite.
Cause of the evolution of heat at Ar_2.	?	Passage of iron from β to α state. Steel becomes magnetic.		Magnetic change.		Separation from the Martensite of an additional amount of Ferrite.
Conditions of Carbon and iron between Ar_2 and Ar_1.	Iron and hardening Carbon.	Carbon diffused in α iron.		?	Carbon and iron combined as $Fe_{24}C$.	Soft steel: Martensite and Ferrite. Medium-hard steel: Martensite. Hard steel: Martensite and Cementite.
Cause of the evolution of heat at Ar_1.	Passage of Carbon from hardening to cement state.	Carbon combining with α iron to form Fe_3C.		Carbon combined with iron to form Fe_3C.	Dissociation of $Fe_{24}C$ and formation of Fe_3C.	Disappearance of Martensite and appearance of Pearlite.
Conditions of Carbon and iron below Ar_1.	Iron and cement Carbon combined as Fe_3C.	Iron and cement Carbon combined as Fe_3C.		Iron and Carbon combined as Fe_3C.		Soft steel: Pearlite and Ferrite. Hard steel: Pearlite and Cementite.
Cause of hardening.	Retention by sudden cooling of the Carbon in its hardening state.	Retention by sudden cooling of a hard allotropic state of iron, which retention is helped by the presence of C.	Retention by sudden cooling of a hard carbide of γ or β iron.	Retention by sudden cooling of a hard sub-Carbide of iron, $Fe_{24}C$.		Retention of the Martensite by sudden cooling.

other change clearly marked. (3) The lower part of Ar_2 showed a further great change from Martensite to Ferrite, with great loss of tenacity. (4) Between Ar_2 and Ar_1 the only marked change was a considerable loss of tenacity and hardness. (5) Ar_1 showed a great change from Martensite to Pearlite, a great loss of tenacity, a slight loss of hardness, a moderate gain in ductility, and a marked change in Carbon condition. (6) Below Ar_1 there was no further change in structure but a considerable loss in tenacity, a great gain in ductility, a great loss in hardness, and a marked change in Carbon condition.

The general results obtained, together with the extraordinary increase in tensile strength on quenching—from 33 tons to nearly 100 tons per sq. inch—Professor Howe considered could not be explained by the direct influence of the Carbon and other impurities present, notwithstanding the high percentage of Manganese and Silicon, and he tentatively suggested that the hardening of steel is due, not to the allotropic β iron alone, nor to the Carbon alone, but to a compound of β iron with hardening Carbon, or what may be called a Carbide of β iron: this has been termed the carbo-allotropic theory.

The hardening of practically Carbonless iron by quenching has been a much debated point, but it must now be taken as proved that even the purest iron, with as little as ·02 per cent. of Carbon and only traces of other metalloids, does undergo appreciable hardening on quenching, although nothing in comparison to that shown by the high Manganese steel used in Professor Howe's experiments. A sample of this pure steel, with ·02 Carbon increased from 19·5 to 29 tons on quenching, and another sample containing ·06 Carbon and less than ·2 per cent. of Manganese, other impurities being very low, gave a maximum stress of 23·3 tons in the normal and 32·2 tons in the quenched state. Whether such hardening bears any distinct relation to the critical points, or whether it is simply a function of the quenching temperature, is still a matter of dispute, and space does not permit of dealing fairly with the controversy, although it has undoubtedly a most important bearing on the allotropic theory.

Table lxix., slightly altered from the table in Mr. Albert Sauveur's paper read before the American Institute of Mining Engineers, September, 1896, summarises the explanations which each of the theories referred to have to offer as to the condition of the Carbon at different temperatures, and the cause of the evolutions of heat at the critical points.

The Solution Theory.—The recent study of the molecular changes occurring during the cooling of carburised iron and of metallic alloys generally, has led to what may be regarded as an extension of the allotropic theory by including in it what is known as the solution theory. It is well known that if common salt is dissolved in water the freezing point of the liquid is lowered. By adding more salt the freezing point of the resulting mixture is continually lowered until the solution contains a certain definite percentage of salt, when still further additions will gradually raise the freezing point of the brine.

It was discovered by Guthrie that the mixture of salt and water which had the lowest freezing point contained about 23·5 per cent. of common salt. A hydrate containing 10 molecules of water would contain 24·5 of Sodium Chloride, and Guthrie came to the conclusion that this mixture with the lowest freezing point was a hydrate of Sodium Chloride of the formula $NaCl + 10H_2O$. He called this and all similar bodies separating from saline solutions at the lowest freezing points *Cryohydrates*, meaning literally cold hydrates or hydrates which could exist in solid state at low

temperatures only. It has since been shown that these Cryohydrates are not definite compounds, but are mechanical mixtures. If we take, therefore, a solution of salt and cool it down by means of a freezing mixture to its freezing point, then if the solution contains less salt than the Cryohydrate, ice will form as soon as its temperature is reduced below the freezing point, and if, on the other hand, it contains more salt than the Cryohydrate mixture, salt crystals will first form. In each case these crystallisations are accompanied by an "arrest" or retardation in the rate of cooling, as shown by a thermometer, and this is due to an evolution of latent heat which marks the commencement of solidification. In the case of the weak salt solution the separation of ice gradually increases the percentage of salt in the mother liquor, while, in the case of the strong solution, the separation of salt decreases the percentage of salt in solution until finally at a temperature of - 22° C. the solution reaches the composition of the Cryohydrate. At this point the remaining liquid then solidifies as a whole, the temperature, as shown by the thermometer in the mixture, remaining stationary until the mass has completely solidified, owing to the evolution of the latent heat of solidification of the Cryohydrate balancing the loss of heat by radiation and conduction.

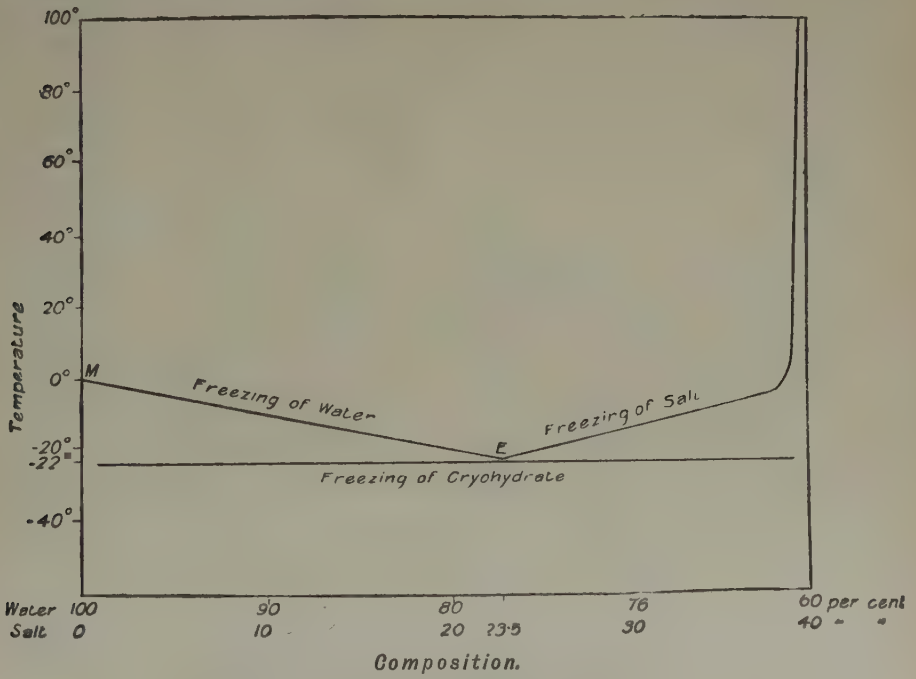


Fig. 250.—Freezing Curve of Solution of Common Salt.

If the cooling be continued after the whole mass is solid the fall in temperature resumes its normal rate.

A frozen saline solution containing less salt than the Cryohydrate will consist of crystals of pure ice surrounded by frozen Cryohydrate, or, if the solution contained a large excess of salt, the frozen mass will be made up of crystals of salt surrounded by solid Cryohydrate.

Fig. 250, showing the freezing curve of a solution of common salt and water, is taken from a paper by Mr. Sauveur in the *Metallographist*, July, 1898.* The abscissæ represent the composition, and the ordinates the temperatures. If we assume that a solution containing, say, 90 per cent. water and 10 per cent. salt is placed in a cooling medium, when it reaches its freezing point ice will form, and there will be a retardation in the rate of cooling denoting an evolution of latent heat, and this temperature plotted on the diagram will give us one point in the curve, M E. By the formation of ice the solution becomes richer in salt, and its freezing point is lowered, and no further separation of ice takes place until its temperature is further lowered, when fresh formations of ice take place, giving us other points in the curve. Thus the curves in fig. 250 are formed by the loci of a number of arrest points of cooling curves until finally the solution becomes richer and richer in salt, and at a temperature of $-22°$ C. it reaches the composition of the Cryohydrate at point E, and solidifies as a whole.

If we now pass from saline solutions to fused alloys, we find the same phenomena exhibited. Let us consider the case of a copper-silver alloy

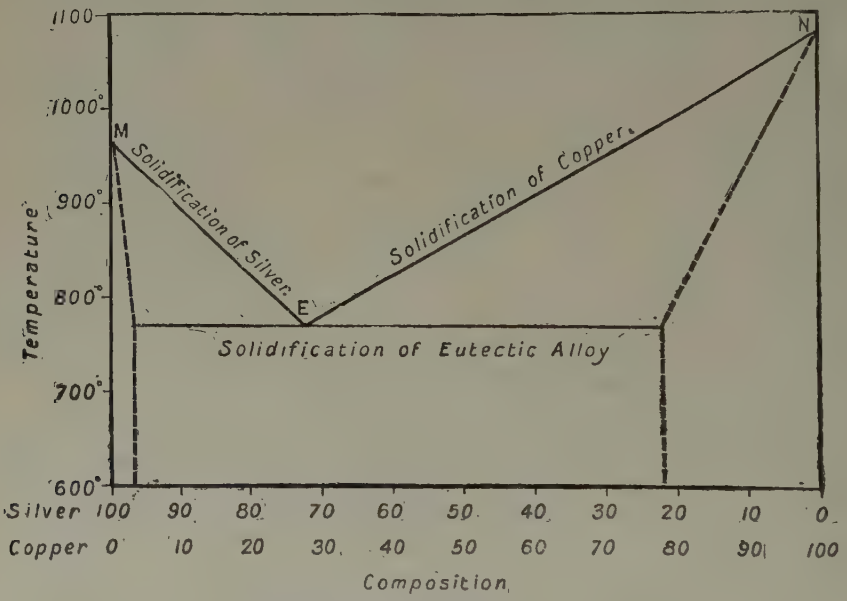


Fig. 251.—Freezing Curve of Copper-Silver Alloys.

(fig. 251), and observe what takes place during the gradual cooling of such an alloy from the fluid state, say, from a temperature of 1,000° C., carefully noting any "arrests" or retardations during the cooling by means of a suitable pyrometer. Any such "arrests" will indicate an evolution of latent heat, marking the beginning of solidification. Assuming the alloy contains 90 per cent. silver and 10 per cent. copper, as it cools down silver will separate out, and the fluid alloy will become poorer in silver and richer

* The maximum amount of salt soluble in water between 0° and 100° C. is rather under 40 per cent., consequently the curve does not extend beyond the point corresponding to this.

in copper, in the same way as the weak salt solution became poorer in water and richer in salt. At each separation of silver there will be an evolution of heat or retardation, the melting point of the fluid alloy will be lowered, and no further separation of silver will take place until there is a further cooling. This separation of silver will continue to give a number of loci of cooling curves for alloys of different composition, which, when plotted, give the curve in the figure, until at a temperature of 778° C., when the alloy has a composition of 28 per cent. copper and 72 per cent. silver, instead of silver continuing to separate the whole of the alloy will solidify at a constant temperature, there being no further reduction until the whole mass is solid, when the temperature again begins to fall. This particular mixture or alloy of silver and copper has the lowest freezing point of all silver-copper alloys, and is called the eutectic alloy, a name suggested by Guthrie. It may be stated that the silver crystals which separate out in these alloys are not

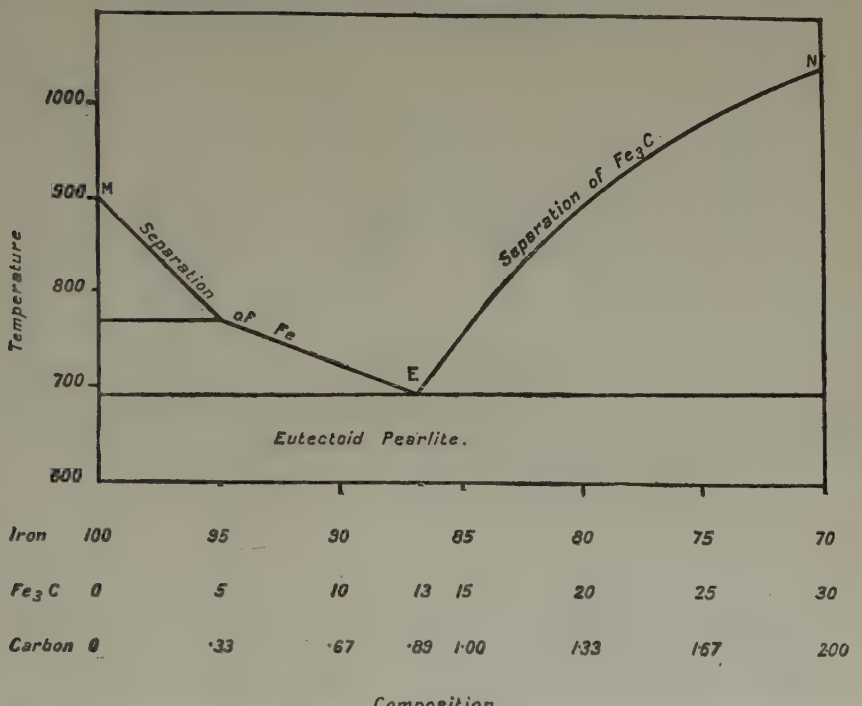


Fig. 252.—Curve showing Separation of Iron and Carbide during the Cooling of Carbon Steels.

pure, but contain up to about 3 per cent. of copper, and in the same manner the copper crystals which separate hold in solid solution up to about 22 per cent. of silver, these proportions are indicated by the dotted lines in fig. 251. The analogy between the eutectic alloy and the Cryohydrates of saline solutions will at once be apparent from the curves.

We must now go a step further, and consider a mixture or alloy of Carbon and iron not in the molten, but in the solid state during cooling from a very high temperature. Let us take the case of pure steel of medium Carbon,

say, about ·6 per cent., which may be regarded for our present purpose as an alloy of iron and Fe_3C. On cooling down such a steel from, say, 1,300°, and carefully observing the rate of cooling by a suitable pyrometer, there is nothing very noticeable until the temperature falls to about 740°, when there is a sudden evolution of heat identical with that which occurred during the commencement of solidification of the silver-copper alloy.

This is the point at which pure iron separates from the solid solution and corresponds to the changes Ar_3 and Ar_2 combined. Subsequent to this at 690° a second point occurs which is the well-known recalescent point, and is analogous to the solidification of the eutectic in the silver-copper alloy, and in passing through it the structure of the steel is entirely changed and many of its chemical, physical, and mechanical properties markedly altered. If we now plot this change point curve (fig. 252) in the same way as we have done for the saline solution and the copper-silver alloy, the great similarity of the curves will be evident. We have two branches of the curve meeting at a temperature of 690°, corresponding to 13 per cent. Fe_3C and 87 per cent. iron; we have also a nearly horizontal line marking the evolution of heat at the recalescent point, clearly indicating some molecular change at a constant temperature. As we are dealing with a solid and not a fluid body, to speak of one of the bodies solidifying, as in the case of copper from the copper-silver alloy, may lead to confusion of ideas, but we may assume that during the cooling there has been a gradual separation of iron until the point E is reached, when a eutectoid alloy of iron and Fe_3C is formed —*i.e.*, a mechanical mixture of these two in the same way as a Cryohydrate is a mechanical mixture of ice and salt, or the copper-silver eutectic, a mechanical mixture of its constituents. If the above hypothesis is right, slowly cooled steel containing less than ·89 of Carbon should be made up of crystalline grains of carbonless iron, surrounded by the eutectoid alloy of Fe and Fe_3C —*i.e.*, Pearlite; steel more highly carburised should be formed of grains of Carbide, Fe_3C (Cementite), surrounded by the eutectoid alloy Pearlite, while metal containing ·89 per cent. of Carbon should consist entirely of the eutectoid alloy. Microscopic evidence shows this to be the case.

To trace the analogy more clearly between the copper-silver alloy and steel we place them in parallel columns.

Copper-Silver Alloy, as shown under Microscope.	Iron Carbide Alloy, as shown under Microscope.
1. Larger percentage of silver than eutectic mixture. Crystalline particles of silver in matrix of eutectic alloy (fig. 253).	1. Larger percentage of iron than eutectoid mixture. Carbonless iron (Ferrite) in matrix of eutectoid Pearlite (fig. 256).
2. Larger percentage of copper than eutectic. Crystalline particles of copper surrounded by, or embedded in, eutectic (fig. 254).	2. Larger percentages of Carbide than in eutectoid mixture. Grains or bands of Carbide (Cementite) surrounded by, or embedded in, eutectoid Pearlite (fig. 257).
3. Alloy of same composition as eutectic when it solidifies as a whole at 778° C. Whole mass entirely eutectic consisting of laminæ (fig. 255).	3. Same composition as eutectoid, ·89 per cent. Carbon. Should consist entirely of eutectoid Pearlite (fig. 258).

On reference to the photographs referred to it will be seen that the above statements are confirmed in every case by the microstructure. We find that fig. 258, illustrating the structure of ·89 Carbon steel, consists entirely of Pearlite, which has the characteristic structure of eutectic alloys, being made up of alternate thin plates of iron and Fe_3C. Fig. 257 shows the

PLATE XVI.—Copper-Silver and Iron Carbide Alloys.

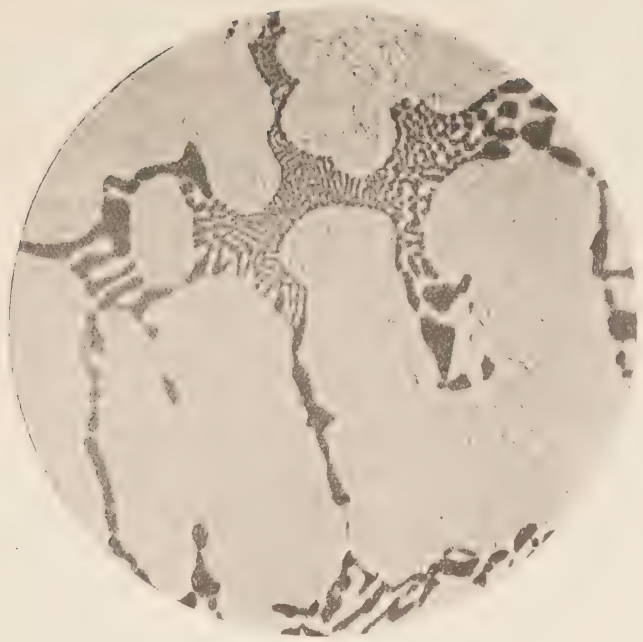


Fig. 253.—Larger percentage of silver than eutectic mixture. Crystalline particles of silver in matrix of eutectic alloy.

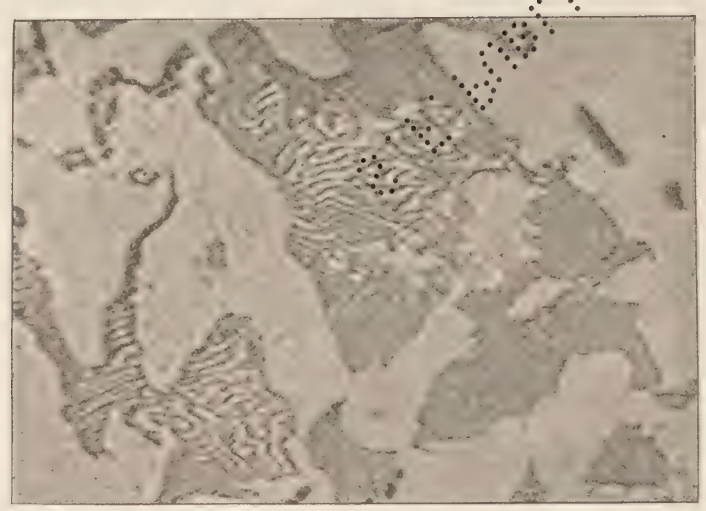


Fig. 256.—Larger percentage of iron than eutectoid mixture. Carbonless iron (Ferrite) in matrix of eutectoid Pearlite.

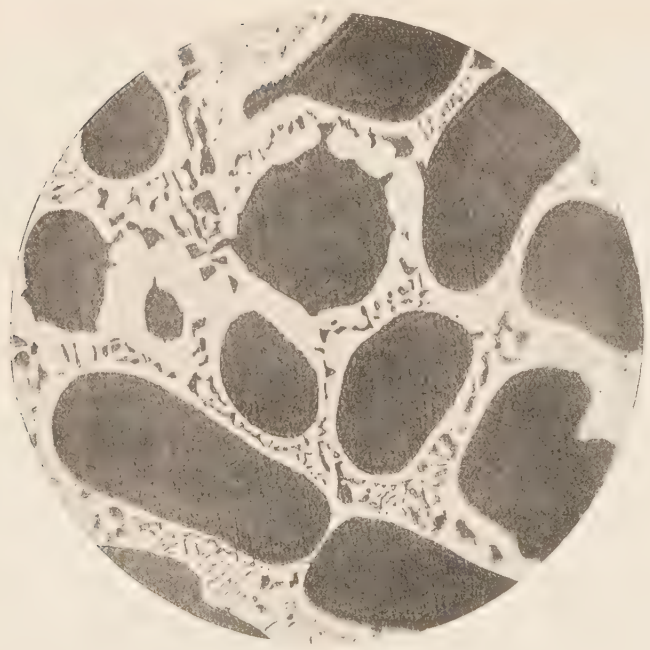


Fig. 254. — Larger percentage of copper than eutectic. Crystalline particles of copper surrounded by, or embedded in, eutectic.

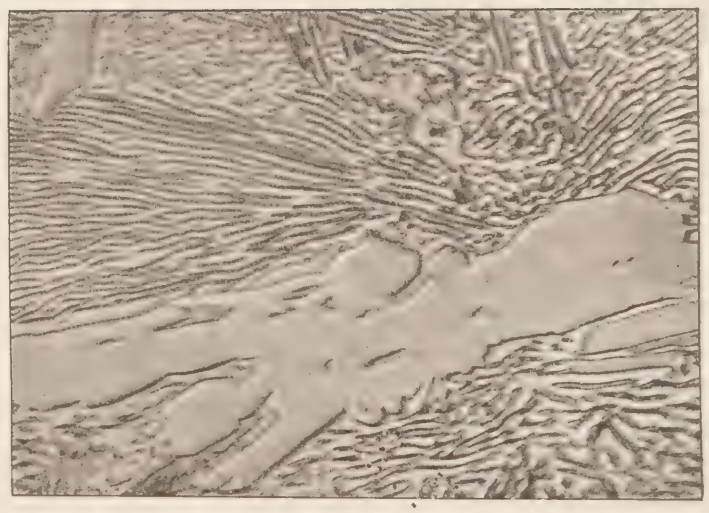


Fig. 257.—Larger percentages of Carbide than in eutectoid mixture. Grains or bands of Carbide (Cementite) surrounded by, or embedded in, eutectoid Pearlite.

Fig. 255.—Alloy of same composition as eutectic when it solidifies as a whole at 778° C. Whole mass entirely eutectic consisting of laminæ.

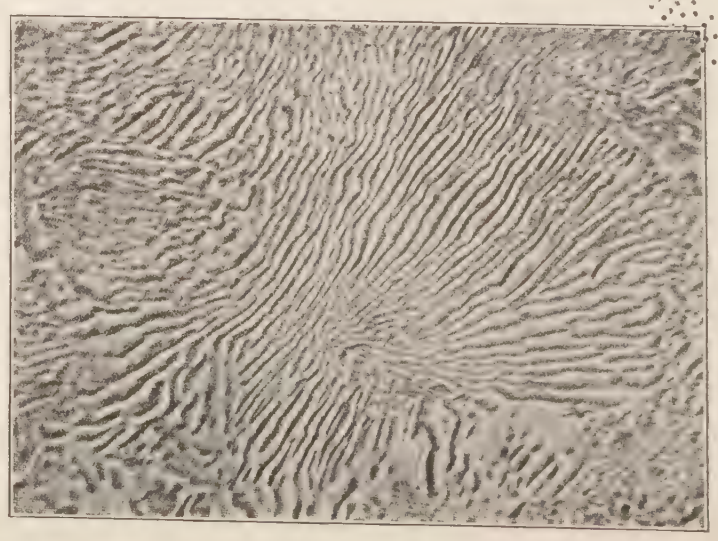


Fig. 258. — Same composition as eutectoid, ·89 per cent. Carbon. Should consist entirely of eutectoid Pearlite. Laminated structure.

Cementite embedded in the Pearlite, and fig. 256 shows Ferrite embedded in Pearlite.

Such are some of the leading considerations which have led to the conception and enunciation of the theory of solid solution, and they are placed before the student that he may understand what is embraced by the term, and the general basis—both on analogy and experiments—on which the theory rests.

The following statement by Dr. Stansfield from his paper read before the Iron and Steel Institute in 1899 clearly defines the position and claims of the solution theory :—

"The solution theory of carburised iron affirms that this substance is, when fluid, a solution of Carbon in iron, and that under certain conditions the solidified mass also forms a solid solution. It further affirms that these liquid and solid solutions obey the ordinary laws of solution, which have been fully studied in the case of aqueous, saline, and organic solutions. (The Carbon may, however, be considered to be in solution as the compound Fe_3C.) The solution theory can, therefore, be invoked to explain both the mode of solidification of carburised iron and the molecular changes that take place after solidification. The experimental data which enable the theory to be applied are mainly afforded by the pyrometer and the microscope used in conjunction with chemical analysis, but all the other chemical and physical properties of carburised iron must be studied, for the sake of the contributory evidence they afford."

Phase Law.—Regarding the liquid and solid alloys as solutions, an interesting point of view from which to consider the changes occurring in them is that of the "phase law" of Gibbs, to which attention has been drawn by M. Le Chatelier and Professor Roozeboom. This, although of great theoretical interest, is too abstruse a subject to be considered in these pages, and the students interested must be referred to papers by Professor Roozeboom, Dr. Stansfield,* and M. Le Chatelier.

* *Iron and Steel Inst. Journ.*, 1900, vol. ii., pp. 311, 317.

CHAPTER XVI.

THE INFLUENCE OF SILICON, SULPHUR, PHOSPHORUS, MANGANESE, ARSENIC, COPPER, TIN, ANTIMONY, ETC., ON THE PHYSICAL PROPERTIES OF STEEL.

As the effects of the different impurities in steel vary very considerably with the percentage of Carbon present, we shall first discuss their influence on mild or structural steel containing ·25 per cent. or less of Carbon, and, in the second place, shall consider how their presence influences the properties of the higher Carbon steels. The questions involved are by no means easy of solution, as, although a large number of experiments have been made by different experimenters, by the addition of known quantities of impurities to different varieties of steel, and most important comparative results have been obtained, it by no means follows that the same amount of impurity present would have the same influence on steel made by a different process, even if the other constituents, as determined by analysis, gave the same results. Again, the temperatures of casting, reheating, and rolling, and the amount of work put upon the material, all have considerable influence, and make it unsafe to draw too sweeping generalisations from small experiments. The costliness of experimenting with large quantities of steel has, with few exceptions, been prohibitive of direct investigations, and consequently we have largely to rely upon results obtained with small ingots. Undoubtedly a great amount of most useful information has been obtained in this way, which, if it cannot be regarded as yielding absolute results, has almost invariably indicated, within reasonable limits, the influence the special impurity would be likely to exert upon the material made under ordinary commercial conditions. The question of the influence of any one particular element on what may be regarded as pure steel is, however, an extremely easy one compared to the question, which has to be faced every day in actual practice, as to what will be its influence when four or five other variables are present, some intensifying and some diminishing the effects due to the particular element under consideration. The tendency amongst engineers is to get over the difficulty by insisting upon a material as free as possible from every constituent other than the Carbon required to produce the requisite hardness, and sufficient Manganese to prevent red shortness. This is without question the right course to take, and there is only one objection to it, and that is, that such material is costly when manufactured on a commercial scale. Except in cases of very high-priced tool steel, steel generally contains more impurities than are theoretically desirable, although there have been great improvements made in this respect during the last few years. The reduced cost of pig-iron and improvements in Siemens practice, both acid and basic, especially the latter, have enabled an extremely pure material to be made, with the greatest regularity, at a cost considerably below that of a comparatively impure material a few years ago.

We will first of all consider the influence of each constituent *per se*, and then discuss the more intricate question of the combined influence of a number of impurities.

The Influence of Silicon on Mild or Low Carbon Steel.

Silicon was for a long time, and is still, by some metallurgists, regarded as having very injurious effects upon the properties of steel, being credited with producing both brittleness and red shortness; but an examination of the facts, especially in the light of recent experiments, certainly does not support these contentions. Over twenty years ago Mrazek, as the result of a set of experiments, came to the conclusion that Silicon, within reasonable limits, had very little influence on the strength, hardness, or brittleness of steel, and that it did not produce red shortness. The systematic experiments of Messrs. Turner and Hadfield most strongly confirm these views, although the latter found that the presence of above ·7 of Silicon was fatal to welding. Professor Turner's* first experiments were made by adding varying quantities of Silicon pig to almost Carbonless steel, obtained from a Bessemer basic blow *before the addition* of Ferro-Manganese, and practically all the samples containing above ·15 per cent. were extremely red short, owing, in the author's opinion, to the more or less over-oxidised nature of the steel; Prof. Turner attributes the red shortness to the Silica and slag formed in the steel by the Silicon reacting with the Oxygen present. The next set of experiments by Professor Turner were made in exactly the same manner from finished basic Bessemer steel, but *after the addition* of the Ferro-Manganese, the content of Silicon varying from ·01 to ·5 per cent. These bars did not show the slightest red shortness at any temperature between a low red and a welding heat, proving, almost without doubt, that the red shortness in the earlier experiments was due to over-oxidised metal rather than to the Silicon present in the alloys. The author can himself vouch for the freedom from red shortness of the second set of bars, as they were tested by plating and welding, under his own supervision, at the works of the Staffordshire Steel Company, Bilston. Table lxx. gives details of mechanical tests and chemical analyses. After making allowances for the variations in the other impurities present, there is practically no increase in maximum stress or in the elastic limit, and no decrease of the reduction of area or elongation until over ·315 per cent. of Silicon is present; and, in fact, only a slight increase in the maximum stress and elastic limit, with corresponding decrease in the extension and reduction of area, becomes perceptable with ·38 Silicon. Even when the Silicon reaches ·5 per cent. there is an increase of only 7 tons in the maximum stress, and a loss of 4 per cent. on the extension in 10 inches.

In 1889 Hadfield† published the results of a most exhaustive series of experiments on the influence of Silicon on mild steel. Taking up the investigation from the point at which Professor Turner had left it, he made a series of alloys from ·7 to 8·8 per cent. In Table lxxi. are given the principal mechanical results obtained by Hadfield The one bar which showed any sign of red shortness up to 5·53 per cent. of Silicon was the first, with only ·24 per cent Si, but this fact is accounted for by the very low content (·14 per cent) of Manganese and the somewhat high per centage of Sulphur, and, in view of the other results, cannot be considered to be in any way connected with the Silicon present. We cannot do better than give a summary of the conclusions Hadfield draws from his own experiments as to the influence of Silicon on steel, both in the forged and cast condition.

* *Journ. Chem. Soc.*, 1887, p. 129.
† *Iron and Steel Inst. Journ.*, 1889, vol. ii., p. 222.

TABLE LXX.—PROFESSOR TURNER'S EXPERIMENTS ON THE INFLUENCE OF SILICON ON MILD STEEL.*

Number of Sample.	Chemical Analysis.					Works Tests.				Mechanical Tests.								
	Silicon per cent.	Carbon per cent.	Sulphur per cent.	Phosphorus per cent.	Manganese per cent.	Rolling.	Hot.	Cold.	Welding.	Limit of Elasticity.		Maximum Stress.		Ratio of Limit to Break.	Extension per cent. on 10 In.	Reduction of Area per cent.	Work done per Cubic Inch.	Relative Hardness.
										Tons per Sq. Inch.	Lbs. per Sq. Inch.	Tons per Sq. Inch.	Lbs. per Sq. Inch.				Tons.	
1	0·010	0·16	0·050	0·060	0·550	Rolled well.	Good.	Perfect.	Perfect.	22·00	...	29·64	...	0·743	23·1	48·8	6·25	Differences so small as to be scarcely perceptible.
2	0·061	0·16	0·028	0·058	0·619	,,	,,	,,	,,	22·21	...	31·61	...	0·703	20·4	40·7	5·80	
3	0·070	0·15	0·084	0·051	0·500	,,	,,	Good.	,,	21·05	...	29·51	...	0·713	22·9	51·5	6·12	
4	0·092	0·21	0·084	0·064	0·634	,,	,,	Perfect.	,,	22·43	...	33·66	...	0·666	19·4	44·1	5·82	
5	0·102	0·18	0·028	0·066	0·662	,,	,,	Good.	,,	21·26	...	33·57	...	0·634	20·6	51·4	6·06	
6	0·121	0·19	0·064	0·068	0·576	,,	Good, but rather red short at welding heat.	,,	Fair.	22·70	...	31·86	...	0·712	21·9	43·7	6·31	
7	0·135	0·13	0·028	0·057	0·480	,,	Good.	,,	Perfect.	21·29	...	29·42	...	0·724	24·8	56·6	6·62	
8	0·247	0·19	0·028	0·074	0·642	,,	,,	,,	,,	22·23	...	34·70	...	0·640	17·6	49·6	5·36	
9	0·320	0·15	0·040	0·081	0·490	,,	,,	,,	,,	22·32	...	33·23	...	0·671	16·7	36·1	4·96	
10	0·382	0·16	0·042	0·087	0·533	,,	,,	Perfect.	,,	24·72	...	35·67	...	0·693	18·0	30·7	5·79	
11	0·504	0·18	0·094	0·121	0·455	,,	,,	Broke short at 50°.	,,	26·35	...	36·72	...	0·717	19·4	34·8	6·45	

* Report of Committee appointed by the British Association, 1888.

TABLE LXXI.—Hadfield's Silicon Experiments.

(To face page 666.

Mark.	Analysis: Carbon per cent.	Analysis: Silicon per cent.	Analysis: Sulphur per cent.	Analysis: Phosphorus per cent.	Analysis: Manganese per cent.	How Ingot Forged.	Whether Tested in Annealed or Unannealed Condition.	Limit of Elasticity: Tons per Square Inch.	Limit of Elasticity: Lbs. per Square Inch.	Breaking Load on Original Area: Tons per Sq. Inch.	Breaking Load on Original Area: Lbs. per Square Inch.	Total Extension per cent.	Reduction of Area per cent.	Bending Test of Annealed Bars, ½ inch wide by ½ inch thick.	Remarks.
A	·14	·24	·08	·05	·14	Fairly well.	..	..	..	..	..	..	..	..	Samples A to D bent double cold, like dead soft steel, and afterwards flattened close without breaking.
A	..	·18	..	..	..	..	Unannealed.	22·00	49,280	33·00	73,920	30·05	54·54	(1) Bent double cold. (2) Bent cold through 180°; radius ⅜ inch, perfect.	
A	..	·20	..	..	..	..	Annealed.	15·17	33,980	25·00	56,000	37·65	60·74	..	This test bar had a black oxidised surface at fracture quite unwelded.
A	..	..	..	..	..	..	,,	15·17	33,980	23·44	52,506	16·90	42·70	..	
B	·18	·79	..	..	·21	Very well.	..	..	..	..	..	..	..	..	
B	..	·70	..	..	..	..	Unannealed.	25·00	56,000	34·00	76,160	29·50	54·54	..	
B	..	·73	..	..	..	..	Annealed.	19·00	42,560	29·50	66,080	34·02	52·66	(1) Bent double cold. (2) Bent through 180°; radius ⅝ inch, perfect.	
B	..	·87	..	..	..	..	,,	19·00	42,560	28·50	63,840	25·45	42·56	..	
B	..	..	..	..	..	..	..	18·16	40,678	27·49	61,578	26·50	66·40	..	
C	·19	1·60	..	..	·28	Very well.	..	..	..	..	..	..	..	..	
C	..	1·60	..	..	..	..	Unannealed.	28·00	62,720	37·50	82,880	31·10	50·58	..	
C	..	1·52	..	..	..	..	Annealed.	25·00	56,000	33·00	73,920	35·10	54·52	(1) Bent double cold. (2) Bent through 180°; radius ⅝ inch, perfect.	
C	..	..	..	..	..	..	..	23·09	51,722	32·50	72,800	24·80	58·30	..	
D	·20	2·18	·06	·04	·25	Very well.	..	..	..	..	..	..	..	..	
D	..	2·11	..	..	..	..	Unannealed.	31·00	69,440	39·50	88,480	15·48	28·02	..	
D	..	2·13	..	.	..	..	Annealed.	25·50	57,120	34·00	76,160	36·50	59·96	(1) Bent double cold. (2) Bent through 180°; radius inch, perfect.	
D	..	..	..	..	..	..	..	20·22	45,293	27·98	62,665	5·60	..	..	
E	·20	2·67	..	..	·25	Very well.	..	..	..	..	..	..	..	..	
E	..	2·69	..	..	..	..	Unannealed.	32·00	71,680	42·50	95,200	17·60	24·36	..	
E	..	2·67	..	..	..	..	Annealed.	24·00	53,760	32·00	71,680	6·05	6·64	(1) Bent double, but broke in radius with last blow. (2) Bent through 180°, but broke off sharp at bend.	
E	..	..	..	..	..	..	..	23·50	52,640	28·52	63,885	2·50	..	..	
F	·21	3·46	..	..	·29	Very well.	..	..	..	..	..	..	..	..	
F	..	3·39	..	..	..	..	Unannealed.	35·00	78,400	47·50	106,400	11·10	14·22	..	
F	..	3·36	..	..	..	..	Annealed.	30·00	67,200	39·00	87,360	8·85	9·28	(1) Bent only to right angle; much stiffer. (2) Broke at 45°.	
F	..	..	..	..	..	..	..	29·45	65,968	34·17	76,541	3·20	5·65	..	
G	·25	4·49	..	..	·36	Very well.	..	..	..	..	..	..	..	..	
G	..	4·18	..	..	..	..	Unannealed.	45·00	100,800	49·00	109,760	·004	·20	..	
G	..	4·23	..	..	..	..	Annealed.	None visible.	..	38·00	85,120	·64	·98	(1) Very brittle; would not bend at all. (2) Broke at 15°.	
G	..	..	..	..	..	..	..	..	..	..	..	..	..	..	Specimen "G" was not quite straight and snapped across the middle with a blow from a hammer while being "set" by the workman. It was evidently very brittle.
H	·26	5·53	·06	·04	·29	Very well.	..	..	..	..	..	..	..	..	
H	..	4·9	..	..	..	..	Unannealed.	None visible.	..	48·00	107,520	·30	·70	..	
H	..	4·8	..	..	..	..	Annealed.	25·00	56,000	25·00	56,000	·37	Broke in thread.	(1) Very brittle; would not bend at all. (2) Snapped in three pieces at first blow of hammer.	
H	..	..	..	..	..	..	..	None visible.	..	38·98	87,315	·70	1·98	..	Test bar broke simultaneously in two places, so that a piece 5 inches long from middle flew right out. This piece itself was nearly separated in two parts by a crack.
I	·04	7·23	..	..	·29	..	..	No test, bar made would not forge.				..	..	..	
J	·08	8·83	·07	·05	·68	..	..	,,	,,	,,		..	..	..	

1. *Forged Condition.*—"The forge reports that the material, A (Table lxxi.) (·24 per cent. Si), did not forge well, cracking somewhat when hammered, but all the other samples, B to H (·79 to 5·53 per cent. Si), when forged at a fair yellow heat, required no special care, thus clearly showing that Silicon, even up to as high as about 6 per cent., does not destroy the malleability of the metal. Upon, however, exceeding this percentage the material is red short, crumbles at a low heat, and, notwithstanding the low percentage of carbon present (·25 per cent.), becomes really a species of cast iron. It should be noted that, if the carbon had been higher, the point at which malleability ceases would have been with a much lower percentage of Silicon. Such red shortness is not removed by the addition of Manganese."

"It may also be mentioned that no return of strength, as is so specially characteristic of Manganese steel, takes place on a further addition of Silicon. Any further addition merely increases its resemblance to silicious cast iron. Nor do gradually increasing percentages, as in the case of Manganese steel, destroy the magnetic properties of the alloy, a 7 per cent. material being apparently as susceptible as ordinary iron or steel drillings."

"Apparently Silicon, up to 1·5 or 1·75 per cent., added to iron, although increasing the limit of elasticity and raising the tensile strength, does not impair ductility, but after this the further increase of tensile strength noticed, is only obtained with a serious loss of ductility. There seems to be no sharp line of demarcation, but, after exceeding 1·5 to 2 per cent., further slight increases cause great changes in the characteristics of the material. In this respect, therefore, its action rather resembles that of Carbon in contradistinction to the action of Manganese, of which larger amounts are required to effect similar changes."

"The annealed flat bending pieces, $\frac{1}{2}$-inch wide by $\frac{1}{4}$-inch thick, gave good results, specimens A, B, C, and D (·24 to 2·18 per cent. Si) bending double cold without fracture, more like soft steel, and after being bent double the pieces were flattened close together cold without showing signs of fracture. Specimen E (2·67 per cent. Si) also bent double cold, but broke in the radius with the last blow. F (3·46 per cent. Si) was much stiffer, bending only to a right angle. G and H (4·49 and 5·53 per cent.) would not bend, and were exceedingly brittle. These bending tests were confirmed by Professor Turner with bars of the same size. Up to D specimen the samples bent to an angle of 180°, with $\frac{1}{8}$-inch radius. Pieces from the bars used for bending tests were also tested for weldability, but entirely without success."

As regards water quenching or hardening, samples A to D (·24 to 2·18 per cent. Si) were unhardened by quenching from even the highest temperature. When plunged at welding heat into specially cold water no hardening beyond a surface stiffening took place, nor was their toughness impaired. Specimen E (2·67 per cent. Si) was heated to a yellow heat and plunged into water at 70° F. This piece was much stiffened, but broke only on being bent double. Another piece, heated to welding heat and quenched in water at 52°, gave a similar result. Sample F (3·46 per cent. Si) was merely stiffened by the same treatment, and was just as brittle as before and had not hardened. In respect to being toughened by water quenching, this material differs from Manganese steel. The heating produced but little alteration in fracture, the crystallisation being still open and coarse. H (5·53 per cent.) quenched both at an ordinary and at a welding heat was merely skin-hardened. These tests clearly prove that Silicon does not confer the same property as Carbon does upon iron—*i.e.*, of becoming hardened when quenched from a high temperature in a cooling medium.

The whole of the samples were subjected even to a welding temperature without falling to pieces.

2. *Cast State.*—As might be expected, the whole of the samples were very free from honeycombs, but this soundness was only acquired at the expense of toughness or ductility. Silicon steel pipes or settles, to a much greater extent than ordinary steel, and this in itself is a considerable disadvantage. Its fluidity, when being poured, is less than that of ordinary steel. The crystallisation or form of fracture of the lower percentages resembles ordinary mild cast steel, but above 2·5 per cent. Si the crystals become very large and glazed, and cleave somewhat after the nature of spiegeleisen. As this large and marked crystallisation increases, the material becomes extremely brittle, and, on further additions, its appearance approaches Silicon pig-iron, and is non-malleable. Considerable shrinkage is caused by high percentage of Silicon in cast or unforged material, but at the same time increase in soundness is obtained.

As in the forged, so in the cast material, when the Silicon exceeds about 2 per cent., and the peculiar crystallisation commences, neither annealing nor water cooling seems to affect the structure.

Taking Hadfield and Turner's experiments together, we may safely conclude that Silicon, when present to a much greater extent than is usually found in mild steel, has no injurious effects on the physical properties. There is one point, however, which must be borne in mind, and that is, that unless specially added, Silicon rarely, if ever, exceeds 0·100 in mild steel which has been carefully manufactured. Its presence in much larger proportion, occasionally, in the case of Bessemer steel points to the fact that, during its manufacture, the "critical temperature" was reached at which the Carbon is oxidised before the Silicon; that it was evidently a "hot blow," and, consequently, the steel was cast at too high a temperature. High Silicon steel made under these conditions is always very unreliable, and this may be one possible explanation why Silicon obtained, and still to a great extent retains, its bad reputation. In cases of the failure of such steels, the high content of Silicon has been considered the cause, whereas the real cause has been careless manipulation during manufacture, high Silicon content being only one of the results.

Hadfield's conclusion that Silicon is prejudicial to welding must be taken as referring to steels with ·7 per cent. and more, and it will not be surprising if such high percentage of Silicon does have a bad influence in this respect, although results obtained by other experimenters with alloys containing several percentages of Silicon have differed from Hadfield as regards the influence of Silicon on welding.

Both Professor Turner's experiments and a great deal of evidence produced by Professor Howe are, moreover, fairly conclusive that much higher percentages than are commercially met with in mild steel do not appreciably affect the welding properties of the metal. Silicon is generally supposed to increase the fusibility of steel, although to a smaller extent than the same percentage of Carbon, and it is possible that it does lower the melting point; but even if this is so, Hadfield found that fluidity, as distinct from fusibility, was decreased instead of increased as might have been anticipated.

The Influence of Silicon on Medium and High Carbon Steels.

We have not any results of systematic investigations, like those of Hadfield on mild steel, to guide us in forming a definite conclusion as to the influence of Silicon on the strength, ductility, &c., of high Carbon steel, and have largely to depend upon the experience of different metallurgists and engineers; but it may be broadly assumed that the higher the Carbon the more the influence of Silicon becomes apparent, although even in high Carbon steels the ductility appears to be influenced only to a comparatively small extent. It is of vital importance that tires, for instance, should not show, under the very severe strains to which they are subjected, the least tendency to brittleness, and steels with from ·2 to ·3 of Silicon and ·5 to ·6 per cent. Carbon have been found to give very satisfactory results. One special brand of tires which has obtained quite a reputation for resistance to wear and general reliability has about this composition, and a special point is made of the Silicon content being from ·3 to ·35 per cent. Professor Howe also gives various analyses of gun steels with from ·2 to ·45 Silicon and ·4 to ·6 per cent. Carbon, which have given good results, and which necessarily have been subjected to shock and very great stress. C. P. Sandberg has experimented with Silicon in steel rails, and has met with considerable success. In their manufacture, he removes the Silicon from the iron as completely as possible, and then adds a known quantity in the form of high-percentage Silico-spiegel or Ferro-Silicon, in this way the percentage of Silicon is easily regulated, and the wearing properties of the steel are found to be greatly improved, this being largely due to the complete removal of gases and Oxide from the steel. Sandberg finds that Silicon up to ·35 per cent. gives good results. With regard to crucible steel for tools, an important and interesting investigation was carried out by Dr. F. C. G. Muller,* from which he concluded that Silicon to the extent of ·8 had no deleterious influence upon the quality of crucible tool steel, and suggested that ·5 or ·6 per cent. of Silicon might actually improve the quality.

Without, however, going so far as this, we may safely say that Silicon for some special Carbon steels is not only not prejudicial, but in certain cases may be beneficial, and in the case of tool steels has no bad effects when present far in excess of that found in ordinary commercial crucible steel. Certain spring steels contain ·45 per cent. Carbon, and up to 2 per cent. Silicon.

Barrett and Brown † examined the Silicon steels made by Hadfield, and found that with an addition of 2·25 to 2·5 per cent. Silicon magnetic permeabilities excelling those of pure iron were obtained. C. F. Burgess and J. Aston ‡ have examined the effect of Silicon on electrolytic iron, and concluded that there is no general improvement in permeability due to the presence of Silicon, but they confirm the experience of practice that a high Silicon alloy, after annealing at high temperatures, is of high permeability for low magnetising forces and densities, such as are used in transformer design. They suggest that in the Silicon steels containing 3 to 6 per cent. Silicon, used in transformer work, the heat treatment is of importance comparable with that of Silicon content. Silicon increases very considerably the electrical resistance of steel, and this is also of considerable importance in transformer working, as it reduces the eddy-current loss.

* *Stahl und Eisen*, vol. vii., pp. 375-377.
† *Journ. Inst. Elect. Eng.*, vol. xxxi., p. 675.
‡ *Met. and Chem. Eng.*, 1910, vol. viii., No. 3, p. 131.

The Influence of Sulphur.

The influence of Sulphur on the tensile strength and ductility is so slight up to ·1 per cent. that, for all practical purposes, its direct action may be disregarded. Webster * credits Sulphur with increasing the tensile strength 500 lbs. per square inch for every increment of ·01 per cent., but the evidence he adduces hardly warrants this conclusion, and he himself admits that the question requires further investigation. The injurious effects of Sulphur, however, are seen during the rolling, a very small percentage causing considerable red shortness, which is noticeable by the ingots or bars cracking at the edges. The amount of Sulphur which may be present without being perceptible during rolling or welding varies with the process by which the steel has been made, the amount of Manganese and copper present, and the temperature of casting. Manganese masks the effects of Sulphur; the higher the percentage of Manganese for a given content of Sulphur, the less the tendency to red shortness. Copper has been credited with acting exactly in the opposite direction, but the experiments of Messrs. Stead and Evans† seem to show definitely that there is no scientific foundation for this belief. For steel required for welding and general structural work, Sulphur should never exceed ·06 per cent., although no signs of red shortness may be apparent when ·1 or even more is present in certain steels. Although, as has been pointed out, Sulphur has apparently no direct influence in the cold on the strength or brittleness of steel, and by some experimenters is even stated to increase its toughness, the real danger of using a high Sulphur steel for structural purposes, even when it has not in any way to be worked hot, lies in the fact that, during rolling, numerous cracks are liable to develop, which, close up, and are quite imperceptible in the finished material. Nevertheless these remain as flaws, and may form starting-points for rupture when the material is subjected to any sudden stress. Thus the contention that, provided the steel is not to be worked hot after it leaves the rolling mill, the percentage of Sulphur is of little or no importance, so long as the bars or plates are free from all visible defects, cannot be admitted for one moment, and probably material of this description is one of the most dangerous that can be employed by the engineer, the more so, that, the tensile strength and ductility, as evidenced by elongation and reduction of area, will give no indications, in the majority of cases, that the material is in any way untrustworthy. In the author's opinion, many of the so-called mysterious failures are due to the original material having been slightly red short during the rolling. Starting with fairly good materials, with careful treatment manufacturers should have no difficulty in producing regularly a steel with about ·06 per cent., and certainly ·08 per cent. is the very maximum that should be allowed in any steel, either for rails or structural purposes. In high Carbon steel, the effect of Sulphur at high temperatures seems to be quite as marked as with mild steel or even more so, but it is rarely present in such large proportion as in the case of mild steel, partly owing to the fact, which has been clearly established, that Carbon in excess has a tendency to expel Sulphur,‡ but still more to the very careful selection of the extremely pure materials used in the manufacture of high Carbon and especially of crucible steel. In the case of the latter also, there is less

* *Iron and Steel Inst. Journ.*, 1904, vol. i., p. 331. † *Ibid.*, 1901, vol. i., pp. 89-100.

‡ Howe (*Metallurgy of Steel*, p. 50) cites instances where, by cementation, Sulphur has been reduced from ·055 to ·019 and from ·04 to ·02, and Percy's experiments were quite conclusive that fusion with excess of Carbon very greatly reduced the Sulphur in cast iron.

danger of absorption of Sulphur from furnace gases, such as exists in the case of Siemens steel, and which is frequently the cause of a very appreciable increase in Sulphur during the conversion of the pig iron into steel.

Sulphur is almost certainly present in more than one form in steel, as it is well known to all metallurgical chemists that, on dissolving some steels in dilute acids, practically all the Sulphur present is evolved in the form of Sulphuretted Hydrogen, whilst others give up only a portion under these conditions, a small percentage being retained in the insoluble residue. No relation, however, has been shown to exist between these two conditions and the physical properties of the steel.

Professor Arnold * first pointed out that the microscope showed that Sulphide of iron exists in steel as (1) globules or ovoids, (2) thin irregular oval laminæ, (3) cell-walls presenting in section a mesh-like appearance, the latter being by far the most dangerous form; Sulphide of Manganese, on the other hand, nearly always occurs as globules or ovoids, very rarely as meshes. An investigation by Prof. Le Chatelier showed that when Sulphide of iron occurs as meshes surrounding the grains of iron, the addition of Manganese breaks up these meshes into globules, probably owing to the formation of Sulphide of Manganese. As Sulphide of iron has a lower melting point than the welding temperature of steel, on heating a high Sulphur steel, the grains in part become surrounded by a more or less semi-fluid Sulphide of iron, which to a great extent explains why such steels are red short. The addition of Manganese breaks up the meshes of Sulphide of iron, and probably replaces them by globules of Sulphide of Manganese, which have a higher melting point. This is Prof. Le Chatelier's rational explanation of the action of Manganese in removing or reducing the red shortness in steel induced by Sulphur. Sulphide of Manganese, although undoubtedly far less injurious than Sulphide of iron, may, however, very seriously affect the physical properties of the material if present in considerable quantities, and especially if aggregated together in patches. These patches are liable to form starting points for cracks which may ultimately develop into fractures under stress.

Many instances are well known of high Sulphur material in rails and other finished sections having given good results over many years of service, and such material on being subjected to drop testing has stood remarkably well; but, in those cases which have come under the author's observation, the Manganese has always been fairly high. On the other hand, such material not infrequently fails under sudden shock, owing, in all probability, to the incipient cracks developed during hot working, which have never completely welded up. There is no doubt that the temperature of rolling has a very important influence on the final mechanical properties of such material in the finished state, and until we are able to adjust the percentage of Manganese in proportion to the Sulphur present, and to control the temperature of rolling so as to insure freedom from these incipient flaws, the only safe course for engineers appears to be to insist upon being supplied with low Sulphur material. Steel containing relatively large percentages of Sulphur appears, as might be expected to corrode more rapidly than low Sulphur steel.

* *Metallographist*, vol. iii., p. 273, 1900. The author greatly regrets that by an oversight this paper of Prof. Arnold's was not referred to in the first edition.

† *Bulletin de la Société d'Encouragement*, September, 1902.

The Influence of Phosphorus.

Of all impurities usually present in steel practical experience has established the fact that Phosphorus is the one that most prejudicially influences the physical properties of the metal by producing brittleness under shock, and general cold shortness. Opinions have been somewhat divided as to its effect on rolling and hot working generally, but it is now generally admitted that this is practically nil when not more than ·2 per cent. is present. Howe * refers to numerous metallurgists who, as the result of proctical experience, have found that up to ·8 or 1 per cent. the influence of Phosphorus is not perceptible during rolling, although others have professed to be able to detect its effects when ·25 to ·3 per cent. is present. The author's experience is that up to ·25 it does not give any indication of its presence in the rolling mill in the case of mild steel, and he has frequently forged under the hammer metal containing 1 to 1·5 per cent. Phosphorus, taken from the basic Bessemer converter during the afterblow, without its showing the least sign of red shortness, although cold it was so brittle that a blow with a small hand hammer would break a ½-inch square rod. For practical commercial purposes, however, Phosphorus in steel should not exceed ·08, and all are agreed that under ·1 per cent. does not affect the rolling properties. If ·1 per cent. or over is present, it tends, however, to produce a finished metal with coarse crystallisation, and low temperature of rolling, slowness of cooling after rolling, and the size of section, &c., have considerable influence in this respect.

The tensile strength may be very slightly increased by small increments of Phosphorus, but between ·05 and ·1 the elongation and reduction of area does not appear to be affected. Campbell † gives a large number of results of mechanical tests on steel angles of the same thickness, containing from ·05 to ·1 of Phosphorus, wh ch show no difference in the elongation or reduction of area; he concludes that small increments of Phosphorus, from ·04 to ·1, cannot be detected in the ordinary testing machine, a conclusion which agrees with the author's own experience. This is a matter of great importance to the engineer, who frequently relies almost entirely upon his mechanical tests, especially upon the reduction of area and elongation, to determine the fitness or unfitness of a material for a given purpose, and it cannot be too strongly insisted upon that a material which may give most satisfactory results in every respect in the testing machine may be high in Phosphorus, and prove highly dangerous when subjected to sudden shock. Cold bending tests with a falling weight (not in a press) are probably among the most practical tests for high phosphoric material, but here again we find the influence of Phosphorus is very capricious, some extraordinarily good results being obtained with material which would be distinctly dangerous, to say the least, for use in structural work. Probably the heat treatment, especially the temperature of rolling and rate of cooling, has very important influence on the ductility of phosphoric steel, and there is very considerable evidence to show that continued, although slight, vibration tends to induce a change in the structure of the metal which renders it quite unfit to resist the application of a sudden shock or stress.

In view of what may be called the treacherousness of phosphoric steel, it is difficult to fix a definite limit for the maximum content of Phos-

* *Metallurgy of Steel*, p. 73.

† *Manufacture and Properties of Structural Steel*, p. 471, 2nd Edition.

phorus which can be safely allowed, but there can be no doubt that the lower this is, the safer the material, and for structural purposes ·06 per cent. is quite as much as can be accepted with a feeling of security. In steel rails ·08 per cent. of Phosphorus may be permitted with safety.

In the case of higher Carbon steels the influence of Phosphorus is much more marked than in low Carbon steels, and Howe* considers that an increase of ·01 per cent. may be detected in 1 per cent. Carbon steel. In the best qualities of crucible steel only the very purest materials are used, the Phosphorus being frequently under ·01 per cent., and it is stated by more than one authority that an increase of ·005 per cent. has a distinct effect on the wearing properties of the cutting edges of tools. In a report to the United States Board on testing iron, the smith's † results showed that out of eighteen samples of tool steels tested there were only three with over ·03 per cent. Phosphorus, and these gave the worst results, as measured by a comparison of the weight of shavings turned, &c., without regrinding the tool, although one with ·025 per cent. gave very good results. The noted Dannemora steel is particularly free from Phosphorus.

The variable influence of Phosphorus on steel may, in part at least, be due to its being present in two or more combinations, and a certain amount of evidence has been brought forward in support of this contention. Cheever,‡ as the result of a considerable number of experiments, came to the conclusion that Phosphorus was present as Phosphide and Phosphate in Bessemer and other steels. It may be admitted as a fact that Phosphorus does exist as Phosphide and Phosphate in puddled steel, but it is very doubtful if the latter is present in ingot metal, and, if it is, it must be in such minute quantities, in proportion to the total percentage of Phosphorus present, that it is hardly conceivable that it could practically affect the physical properties of the metal. It is a well-known fact, however, that Phosphorus is present in steel in two distinct forms, and when the steel is dissolved in dilute Hydrochloric Acid one of these is evolved as Phosphoretted Hydrogen, and the other remains behind in solution or with the residue. Baron Hanns Jüptner von Jonstorff§ gives the results of some experiments on wrought iron and steel, and comes to the conclusion that the cold shortness caused by Phosphorus is due to that portion of the Phosphorus which is evolved as PH_3, and which is more or less evenly distributed through the steel while the insoluble residue left as Fe_3P, Mn_5P_2, and MnP is comparatively harmless.

Although some of the analyses he gives tend to show that as the percentage of Phosphorus evolved as Phosphoretted Hydrogen increases, in comparison to the total Phosphorus present, so does the cold shortness, his results are too few and not sufficiently concordant to warrant his somewhat sweeping conclusions. It is quite possible that further experiments may confirm his hypothesis, and his paper is a most suggestive one well worthy of the attention of all metallurgists, but a vast amount of work requires to be done before it will be safe to generalise on this very important matter.

* *Metallurgy of Steel*, p. 69.
† Report U.S. Board on the Testing of Iron, &c., 1881, vol. ii., p. 592.
‡ *Trans. of American Inst. Mining Engineers*, vol. xv., p. 448.
§ *Iron and Steel Inst. Journ.*, 1897, vol. i., p. 225.

The Influence of Manganese.

In considering the influence of this metal on steel it must be remembered that, unlike most of the other constituents, it is not an impurity originally present which the metallurgical treatment has failed to remove, but is, at all events in the case of all steel used for structural purposes, an essential constituent especially added to deoxidise the decarburised metal so as to prevent its being red short. The effect which Manganese has upon the tenacity and ductility varies very considerably with the percentage of Carbon in the steel, its influence being much more marked in the case of high than of low Carbon steels. In the author's opinion, for mild steel and rail steel, the less Manganese a steel contains above that required to insure solid ingots and freedom from red shortness the better, and, provided that good pig-iron free from sulphur is used, and reasonable care taken during the manufacture, there should not be the slightest difficulty in obtaining these results with ·4 to ·5 per cent of Manganese in the finished product, at all events for mild steel made in the Siemens furnace. In the case of rails which are still very largely made by the Bessemer process, it is difficult, owing to the large additions necessary to obtain the required content of carbon, to keep the Manganese down to this limit, and provided it does not exceed ·8 per cent., the metal may be expected to give good results. The general tendency of Manganese is undoubtedly to increase the tensile strength and somewhat to reduce the ductility, but neither of these effects is nearly so great as has often been maintained by many metallurgists, and a slight increase in Carbon, or other constituents accompanying the Manganese, is very often responsible for a greater part of the increase, and for the very varying results obtained. The fact that many thousands of axles and tires are made every year with 1 per cent. of Manganese shows that, up to this point, it does not reduce the ductility so as to induce brittleness to any dangerous extent, as, notwithstanding the severe strains that such material is subjected to, failures are comparatively rare. It must be borne in mind, however, that both axle and tire steels are made from very high-class material most carefully selected, and the greatest care is taken during manufacture to insure the uniformity of composition of the finished material. In the case of mild steel required for boiler plates, and for bridge or other structural work, an increase of Manganese has a very distinct hardening effect, and above ·6 per cent. begins to be dangerous and should not be allowed. The tendency amongst steel makers to bring up the tensile strength to the specification by increasing the Manganese, instead of the Carbon, is greatly to be deprecated, and notwithstanding the reported excellent records of mild steel plates with 1 per cent. of Manganese, and steel rails containing more than this amount, engineers will be well advised to decline to accept such material. Webster,* from a large series of test bars, came to the conclusion that, in the case of mild steel, the effect per unit of Manganese on the tensile strength decreased as the percentage of Manganese increased, and whereas an increase from ·25 to ·3 per cent. of Manganese raised the tensile 1,000 lbs. per square inch, an increase from ·55 to ·6 raised the tensile only 500 lbs. This may be so, and probably 1,000 lbs. per square inch increase for every $\frac{1}{10}$ per cent. Manganese is not far from the truth, although other experimenters have found less, and Campbell † gives a series of tests showing that the addition of ·2 per cent. of Manganese does not appreciably affect the tensile strength.

* *Iron and Steel Inst. Journ.*, 1894, vol. i., p. 331.
† *Struct. Steel*, p. 266.

The influence of Manganese on high Carbon steels required for tools is much more marked, and if present in any quantity it is very liable to cause fracture on quenching. The highest class tool steel rarely contains more than ·3, and frequently less, and although numerous instances are on record where steels with ·4 and ·5 of Manganese have given excellent results, it is decidedly safer to keep the Manganese low, and there is no reason, even from a manufacturer's point of view, for having a high Manganese in such steels. The influence of large percentages of Manganese—viz., from 2 per cent. and upwards—will be dealt with under the head of special steels.

The Influence of Arsenic.

In 1888, Mr. A. E. Tucker and the author * made a series of experiments on the effect of Arsenic on mild steel, and came to the conclusion that up to ·17 it had no effect upon the ductility or tenacity of the steel, and that elongation and reduction of area was likewise unaffected, but that above this limit cold shortness was slightly noticeable and gradually increased. It was also found that, up to 1 per cent., Arsenic produced no red shortness at rolling temperatures, but that, above ·17 per cent., the influence on welding was distinctly marked, and above ·25 per cent. the steel refused to weld. In 1895, Stead,† after a most exhaustive investigation, practically confirmed these results. He sums up his results as follows:—That between ·1 and ·15 per cent. of Arsenic in steel for structural purposes has no material effect on mechanical properties, such as tenacity, ductility, &c., as shown by bending and tensile tests, but that its influence is just noticeable with ·2 per cent. The rolling and forging properties are not affected in the slightest degree by considerable percentages of Arsenic, but welding is made more difficult by even very small quantities. The only points where Mr. Stead's results disagreed with those of Mr. Tucker and the author were in the quenched samples, in which Mr. Stead found that the arsenical steel bent better after quenching than before. This is a point which requires further investigation, as Professor Arnold's tests show that quenching had a distinctly hardening effect. Mr. Stead found the influence of large quantities of Arsenic to be less than was indicated by earlier experiments, and, as his were far more exhaustive, he is probably correct in this respect. In any case, Arsenic in such proportion as it is usually present in commercial steel—*i.e.*, up to ·1 per cent.—is not in any way prejudicial, except when the steel is required for welding.

The Influence of Copper.

The influence of Copper on steel was formerly greatly exaggerated. Whereas it was considered to be very harmful, it is now known, when present in small quantities, to have no serious influence on the physical properties of steel.

According to a statement in Professor Howe's *Metallurgy of Steel*,‡ an American firm of steel rail makers habitually made Bessemer T rails with ·51 to ·66 per cent. Copper, and they were so slightly red short that, in spite of their thin flanges and the exceptionally low temperature at which they were finished, only from 1·25 to 2·5 per cent. of them were so defective as to be classed as second quality.

* *Iron and Steel Inst. Journ.*, 1888, vol. i., p. 183. † *Ibid.*, 1895, vol. i., p. 108.
‡ *Metallurgy of Steel*, p. 83.

According to a communication by M. A. L. Colby,* neither a propeller shaft with ·565 per cent. Copper nor a gun tube with ·553 per cent. showed any defects after forging and hardening, and armour plates with ·575 per cent. flanged well and answered all the requirements of the American Navy. Various samples of Bessemer steel, with Carbon ranging from ·11 to ·65 per cent. and with ·292 to ·486 per cent. Copper, showed no red shortness on rolling. His experience also tended to show that Copper had but little tendency to liquate.

Messrs. Stead and Evans† have carried out a valuable series of experiments on the influence of Copper on steel rails and plates, partly with a view to break down the prejudice with which engineers have been wont to regard Copper in steel. Ladles of steel were divided into two parts, to one of which Copper was added, and ingots from both were then cast, rolled, and subjected to similar tests. The Copper added ranged from ·5 to 2 per cent. In each case the steel containing Copper rolled equally as well as that without, except in the case of the 2 per cent. sample, which was afterwards found to be overheated. The authors conclude that a steel containing a high percentage of Copper, although not red short in the ordinary sense, yet will not bear the same amount of heat as the same metal without Copper, thus showing that the effect of the latter resembles that of Carbon rather than that of Sulphur.

The cupreous samples showed a slightly increased tensile strength, a somewhat higher elastic limit, and less elongation, and (with one exception) less contraction of area. They stood percussive tests as well as the normal metal, and the bending tests and welding tests showed no difference. The investigators conclude that Copper does not possess the property of making steel red short.

Experiments by Muller‡ and Dillner§ confirm the results obtained by other investigators as to the non-injurious effect of Copper on the physical properties of steel. Up to ·62 per cent. it somewhat increases elasticity, strength, and hardness, without appreciably affecting the elongation, and no red shortness is observable during rolling or forging. In the case of harder steels containing ·5 per cent. of Carbon the toughness of the metal is diminished, and on quenching in water the steel showed considerable brittleness.

Messrs. Stead and Wigham‖ have also investigated the influence of Copper on steel wire. The Copper in the steels experimented with varied from ·46 to 2 per cent. The conclusion arrived at, from an examination of the mechanical properties of these steels, was that Copper in such large quantities did not improve the quality of the wire, but generally had a deteriorating influence, particularly in the presence of high Carbon. The only apparent useful property the cupreous steel wire seemed to possess was that it was not so readily corroded as the non-cupreous material.

In a separate communication on the alloys of Copper and iron, Mr. Stead¶ shows that, on melting with Charcoal, alloys containing more than 7·5 per cent. Copper, Copper containing about 3 per cent. of iron is thrown out of solution and falls to the bottom, leaving a layer of carburised iron on the surface containing about 7·5 per cent. Copper. This action of Carbon, in throwing Copper out of solution, probably accounts for some of the conflicting results obtained with iron alloys of this metal.

* *Stahl und Eisen*, 1900, pp. 20, 55.
† *Iron and Steel Inst. Journ.*, 1901, vol. i., p. 89.
‡ *Stahl und Eisen*, vol. xxvi., p. 1444-1447.
§ *Ibid.*, vol. xxvi., pp. 1493-1495.
‖ *Iron and Steel Inst. Journ.*, 1901, vol. ii., p. 122.
¶ *Ibid.*, 1901, vol. ii., p. 104

C. F. Burgess and J. Aston * have also examined the properties of iron-copper alloys, and found that the alloys up to 2 per cent. Copper forge well at red heats. Those from 2 to 7 per cent. Copper will not forge at a low temperature, and rather poorly at a white heat, the ease of workability varying inversely as the percentage of copper. The same authors,† on examining the magnetic and electrical properties of these alloys, found that above 2 per cent. Copper the permeability falls off rather rapidly as the Copper content is increased, but only bars of 4 per cent. and more are conspicuously poor. Annealing greatly improves the quality of the bars. The authors consider that there is nothing to be feared from the effect on the magnetic properties of the small quantities of Copper ordinarily found in commercial steels. The electrical resistance is found to increase to a maximum at a Copper content of 1·51 per cent.

The Influence of Other Impurities.

Antimony.—As might be expected from the physical properties of Antimony, its presence in steel seems to be highly detrimental. No very recent information, however, appears to be available. It is said to make iron both red and cold short, even when present in very minute quantities. It is seldom present in iron ores, and when added to steel largely passes out again at the melting point of steel.

Bismuth.—Bismuth appears to act very much like Antimony, and to have nearly as detrimental effects on the properties of the steel into which it is introduced.

Calcium.—Although the influence of Calcium on steel is unknown, it is interesting to note that, according to some recent investigations of Mr. G. Watson Gray, Calcium is often present in high grade Ferro-Silicon made in the electric furnace. We quote some partial analyses from samples of this material:—

	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Silicon, . . .	31·90	44·05	56·70	62·90	68·65	78·80
Iron, ...	61·30	45·28	26·70	24·40	9·91	12·64
Manganese, . .	3·92	3·51	2·40	1·10	0·20	0·30
Aluminium, . .	0·22	0·47	3·52	1·52	2·40	4·76
Calcium, . . .	0·79	3·29	7·12	6·96	14·40	2·32
Magnesium, . .	0·26	0·44	0·38	0·32	0·31	0·22
Carbon, . . .	0·50	0·52	0·63	0·33	1·03	0·55

Nickel.—The influence of Nickel is considered in connection with special steels.

Cobalt.—Hardly any experiments have been made in this direction. It is probable that the effects of Cobalt on steel would be distinctly advantageous. In some early experiments, quoted by Percy, alloys of iron with high percentages of Cobalt were found to be brittle.

Tin.—Tin will alloy with iron in all proportions, but, for engineering purposes, the alloys are of no practical importance. Iron or steel sheets coated with Tin form the well-known *tinplate*, an article of immense importance in commerce. Generally, it may be said that the presence of small percentages of Tin is detrimental to iron, and, on the other hand, the presence of a small percentage of iron in Tin as detrimental to the Tin.

* *Electrochemical and Metallurgical Industry*, 1909, vol. vii., pp. 527-529.

† *Ibid.*, 1910, vol. viii., pp. 23-26.

Some recent experiments on the addition of small amounts of Tin to iron have been published.* Samples of iron containing from ·1 to ·63 per cent. of Tin were prepared and tested. It was found that all the samples forged well, though they were somewhat hard; all the samples rolled, but split somewhat at the edges; they welded well, except the one with the highest percentage of Tin (·63 per cent.); the bending tests, both hot and cold, were satisfactory. The Tin was found to be irregularly distributed in the ingots. Samples of crucible steel were also prepared containing ·23, ·5, ·68, and 1·62 per cent. of Tin. All these samples forged well, except the last, which was somewhat red short; none of them, however, would weld.

In a charge of basic open hearth steel, into which Tin had been accidentally introduced, Zugger found ·55 per cent. Tin, ·015 per cent. Antimony, ·03 per cent. Arsenic, and ·182 per cent. Copper. This metal was found to roll quite satisfactorily into plates; on further rolling into sheets, however, cracks developed at the edges. Bars rolled from the metal bent close under the cold bending test, and gave a tensile strength of 40 kilos. per sq. mm., with an extension of 31 to 34 per cent. on 7·5 cm. From these experiments it would appear that Tin above $\frac{1}{2}$ per cent. materially affects the welding properties of steel, but does not affect the tensile or extension tests.

Zinc.—The effect of Zinc on the mechanical properties of steel is of no practical importance, and the only useful application of the alloys of iron and Zinc is in ordinary galvanising of sheets and other articles of commerce. In such articles there is a superficial alloying of Zinc with the steel or iron used. Alloys of iron and Zinc, containing about 10 per cent. of iron, are formed during the galvanising process in the Zinc pots, and are known as hard spelter, but on account of the easy volatility and the feeble affinity of the two metals, the greater part of the Zinc is removed on heating such alloys to a white heat. When Zinc is added to molten steel only minute traces of it remain in the metal, but if a rod of steel is immersed in a bath of Zinc, at high temperature, the steel is attacked with the formation of an alloy. This action is greater on high Carbon steel than on low Carbon steel, and recently Messrs. John Lysaght & Co. tried some experiments by immersing steel bars containing respectively 1·0 per cent., 0·5 per cent., and 0·1 per cent. of Carbon in the same Zinc bath, with the result that the bars containing 1·0 per cent. after a week were found to have entirely disappeared, those containing 0·5 per cent. had wasted to about one-half their original size, while the bars containing 0·1 per cent. were practically unattacked. Under certain conditions, however, mild steel is very seriously attacked by Zinc, and the author is aware of one case in which a galvanising pot made of mild steel plates was practically destroyed in twenty-four hours due to overheating.

Segregation.

In considering the influence of the various impurities on the mechanical properties of steel, the unequal distribution of such impurities is of the greatest importance. This is one of those matters which steel makers often find it convenient to ignore, but it is so well known and generally recognised that it is necessary to face the facts, and to carefully consider the conditions which favour the segregation of impurities from the mass of the metal, and their concentration in different parts of the ingot. It is also an important point to be considered by engineers in drafting specifications, both in their own interests and in fairness to manufacturers, as even in the highest quality of steel, made with the greatest care, there will always be some slight variation in the composition of the material between the centre and

* *Stahl und Eisen*, vol. xxi., p. 330.

the outside of the ingot, and, if reasonable allowance is not made for this, it may lead to rejection and cause considerable trouble to all concerned.

In the gradual cooling of large masses of impure metal and metallic alloys, there is always a tendency for certain constituents to separate or segregate and concentrate in certain portions of the mass, and this has a most important bearing on the homogeneity of steel ingots. This matter, in relation to steel, was first investigated by Stubbs* and Snelus† in 1881, and since then has received considerable attention from both practical and scientific men. Steel may be regarded as a complex alloy in which the impurities present, such as Silicides, Phosphides, Carbides, Sulphides, &c., are dissolved in the iron. These different bodies will vary in their freezing or solidifying points, some remaining fluid much longer than others, and all having a lower freezing point than the metallic iron, and eutectics are also formed with various impurities which have still lower freezing points. Consequently, those having the lowest melting point will tend to gradually segregate from the iron and concentrate in the hottest part of the ingot, which will naturally be towards the centre, as the ingot is rapidly being cooled from the outside by contact with the cast iron mould. This tendency is modified by various forces, some acting with and some against it, and will be largely affected by the initial temperature of the molten mass, rapidity of cooling, &c. *Other things being equal,* the more rapid the cooling, the less the segregation, and, as rapidity of cooling will largely depend upon the size of the ingot, the smaller the ingot the less segregation there will be.

Professor Howe‡ divides bodies which tend to separate or segregate into three groups:—

"1. Compounds which differ much in fusibility from the rest of the mass.

"2. Compounds whose components have a strong affinity for each other, and which hence tend strongly to form during cooling.

"3. Compounds which differ greatly in density from the rest of the mass."

The proportion in which the segregating body is present will largely affect the result: the higher the impurities in the steel ingots the greater the segregation. Carbon and Phosphorus having a greater affinity than Manganese for iron, and the Carbides, Phosphides, and Sulphides of iron being more fusible and of lower density than the alloys of iron and Manganese, the former should segregate more readily than the Manganese, but the segregation of the latter is favoured by its being present in much larger proportion. There is no doubt that the Manganese also combines with the Sulphur and Carbon, and so segregates to some extent as Sulphide and Carbide.

It is generally found that segregation of one impurity means, more or less, the segregation of all, although this is not always the case. From a large number of results given by Professor Howe, it would appear that Carbon is the element which segregates most readily, but this is probably largely due to its generally being present in much larger proportion than other constituents, except Manganese. In the author's experience, Sulphur and Phosphorus are the elements which are generally found most unequally distributed, especially when the steel contains a somewhat high percentage of these. When there is any appreciable segregation of Manganese, Sulphur is generally found, and it is probable they liquate together as Sulphide of Manganese.

The rapid cooling of the outside of an ingot prevents any separation of impurities occurring there, but the centre of the ingot remaining fluid for

* *Iron and Steel Inst. Journ.*, 1881, vol. i., p. 199. † *Ibid.*, vol. ii., p. 379.

‡ Howe, *Metallurgy of Steel*, p. 205.

a considerable time, the segregated matter travels inwards, assisted somewhat by the contraction of the metal. The impurities, being specifically lighter than the iron, tend at the same time to rise to the top of the ingot.

Numerous analyses of drillings taken from different parts of steel ingots have shown that the centre and top of the ingot always contain the larger proportion of impurities, and this somewhat fortunate concentration in a particular part of the ingot enables the steelmaker to remove this impure portion during manufacture much more readily than he could do if the impurities were irregularly distributed through the entire ingot. Thus in rolling rails and various sections, the top end of the ingot can be removed by shearing, and in special cases, such as the manufacture of guns or for other exceptional purposes, the centre of the ingot can be bored out. So important is it considered not to interfere in any way with this natural concentration of the impurities, that many American engineers specify in their rail and other specifications that the ingots are to be conveyed from the casting pit, and reheated in the vertical position, to assist the segregation of the impurities towards the top of the ingot.

From a very large number of analyses collected and tabulated by Professor Howe,* it is shown that it is by no means unusual in bad cases of segregation to find a difference of 50 per cent. or more in the impurities in different parts of the same steel ingot or finished section. This applies equally to rails, bars, plates, &c. Such examples of segregation are, however, abnormal, and usually occur only when the original impurities present are high, and when the temperature of casting has been much higher than it should have been, as is frequently the case when very siliceous metal is blown and the charge is not cooled sufficiently by scrapping. In the author's experience, practically all cases of exceptionally bad segregation have been due to some such cause as the above, especially when casting in large ingot moulds has still further facilitated the liquation.

When steel is cast in very small ingot moulds, as in the case of crucible steel, practically no segregation occurs, but the casting of steel in large masses does undoubtedly favour unequal distribution.

Provided that care is taken in the manufacture, and that the temperature of casting is kept well under control, although there will always be some segregation, it should not be a really serious matter in the case of the highest qualities of steel. In the case of rail steels and similar qualities, it is, however, always liable to occur to a greater extent than is desirable.

In Chrome and Tungsten steel there seems considerable liability to segregation, whereas Nickel steels, especially those which contain a large percentage of Nickel, are usually remarkably uniform in their composition.

Talbot † made an exhaustive examination of segregation in acid and basic steel ingots, with and without the addition of Aluminium. He concluded that in ingots to which no Aluminium has been added, excessive segregation occurs down the central portion of the ingot, from about 6 inches from the top to half-way down, that Sulphur tends to segregate most, Phosphorus next, then Carbon, and finally Manganese, the segregation of which is so slight as to be almost negligible. The effect of the addition of 4 ozs. of Aluminium per ton was to immediately reduce the amount of segregation, as will be seen from the following figures, taken from analyses of borings from the centre and outside of acid steel ingots.

The borings were taken from top to bottom at distances of 6 inches, and the ingots measured 18 inches × 22 inches × 67 inches.

* *Metallurgy of Steel*, p. 206.

† *Iron and Steel Inst. Journ.*, 1905, vol. ii., p. 204.

ANALYSES TAKEN FROM CENTRE AND OUTSIDE OF TWO INGOTS, FROM TOP TO BOTTOM, AT DISTANCES OF 6 INCHES APART.

No.	Without Aluminium.						With Aluminium.					
	Centre.			Outside.			Centre.			Outside.		
	Sulphur.	Phosphorus.	Carbon.	Sulphur.	Phosphorus.	Carbon.	Sulphur.	Phosphorus.	Carbon.	Sulphur.	Phosphorus.	Carbon.
Top.												
1, .	·053	·051	·41	·035	·047	·33	·038	·035	·32	·067	·054	·39
2, .	·049	·052	·39	·031	·034	·32	·042	·040	·35	·066	·057	·39
3, .	·267	·197	·95	·018	·030	·31	·078	·061	·48	·065	·056	·39
4, .	·141	·109	·59	·027	·036	·32	·086	·063	·43	·066	·055	·40
5, .	·097	·083	·47	·034	·040	·35	·081	·049	·34	·068	·067	·41
6, .	·081	·065	·46	·036	·046	·37	·059	·054	·38	·066	·058	·42
7, .	·056	·061	·46	·040	·048	·38	·067	·052	·38	·064	·057	·41
8, .	·056	·053	·38	·041	·046	·38	·057	·049	·36	·058	·052	·41
9, .	·043	·045	·35	·039	·044	·36	·053	·049	·36	·058	·056	·40
10, .	·048	·047	·35	·044	·046	·38	·056	·050	·36	·056	·056	·38
11, .	·047	·045	·34	·048	·048	·41	·057	·047	·37	·060	·053	·38
12, .	·051	·050	·39	·053	·054	·43	·056	·049	·38	·065	·054	·39
Bottom.												

The average analysis of all the drillings taken from the ingot to which no Aluminium had been added was **S** ·059, **P** ·055, **C** ·41; and the average analysis of all the drillings from the ingots to which Aluminium had been added was **S** ·060, **P** ·052, **C** ·39. There can be no doubt, therefore, that constituents whose presence is injurious to the mechanical properties of steel find their way towards the top centre of the ingot. In steel ingots destined for the manufacture of guns it is usual to cut off the tops, which are unsound as well as impure, and in some cases to bore out the centre of the ingot. For similar reasons, it is now customary to cut off the "crop" ends of steel rails. The importance of this procedure has been widely recognised,* and the effect of segregation must be carefully considered in making large castings and forgings.

Various methods have been introduced for compressing steel ingots while still in the fluid state, with a view of preventing segregation and lessening the amount of blowholes produced during the solidification. Casting under pressure was first attempted by Bessemer in 1856, but was re-introduced and rendered practicable by Whitworth in 1865†; more recently the Harmet‡ process of compressing steel ingots during solidification in vertical taper moulds, and the Robinson and Rodger§ method of horizontal compression, have been introduced with considerable success, and both methods are successfully employed in various steel works. All these methods very largely produce the desired results, giving greater homogeneity and freedom from blowholes, and greatly reducing the amount of cropping necessary.

* Maitland, *Min. Proc. Inst. C.E.*, vol. lxxxix. (1887), p. 127. See also Eccles, *Journ. Iron and Steel Inst.*, No. 1 (1888), p. 70, and the discussion on Greenwood's paper, on the "Treatment of Steel by Hydraulic Pressure," *Min. Proc. Inst. C.E.*, vol. xcviii. 1889.

† Patent No. 3018, 1865. ‡ *Journ. Iron and Steel Inst.*, 1902, vol. ii., p. 146.

§ Capron, *Journ. Iron and Steel Inst.*, 1906, vol. i., p. 28.

Occlusion of Gases by Iron and Steel.

The retention or occlusion of gases by iron was first shown by Graham,* and Parry, on repeating his experiments, obtained most surprising results, especially in regard to the amount of Hydrogen present. More recent investigations by Stead, Muller, and others have shown that although large quantities of Hydrogen, amounting occasionally to five or six times the volume of the steel, are present, that the very large quantities obtained by Parry in some cases were so abnormal as to lead to the opinion that some error must have been made by him, and that the large volumes found could hardly have come from the steel. The presence of this gas, as well as Nitrogen and Carbon Monoxide, in steels at ordinary temperatures is best demonstrated by heating the steel *in vacuo* or by drilling the steel under water or Mercury. A very distinct odour may often be noticed when drilling many kinds of steel, which suggests the presence of these elements in some form which may admit of formation of Hydrocarbons or combination of Hydrogen and Nitrogen.

The difficulty of estimation has led to very various results. Muller † found from 25 to 60 volumes of gas in samples of steel by drilling them under water, while Stead, working on different samples, and drilling under Mercury instead of water, obtained a very small quantity of gas. It has been suggested that the high results obtained by Muller were due to the decomposition of the water, but as no appreciable amount of Oxygen was found in the cooled gases, this could not have been the case, as it is clear that had the Hydrogen been derived from the water, Oxygen would have been liberated at the same time.

A. H. Allen, ‡ many years ago, determined the percentage of Nitrogen in a number of steels, and his results have since been confirmed by the author and Mr. Twynam, § and as much as ·027 per cent. was found in some cases. The conditions under which Carbon Monoxide and Dioxide are occluded in steel are obscure, but there seems no doubt that Carbon Monoxide, probably derived from the reaction with the Manganese additions, dissolves in steel to some extent.

In an appendix to his paper on the "Determination of the Allotropic Changes of Iron by the Measurement of the Variations in Electric Resistance," Boudouard ‖ gave some analyses of the gases given off on heating different varieties of steel *in vacuo*. Among the gases so examined were Carbonic Oxide, Hydrogen, Nitrogen, and Oxygen, which he found in Carbon and some Chrome steels, whilst from steels containing Tungsten, Manganese, and Nickel he obtained no gas.

G. Belloc ¶ has examined the relation between the temperature and the rate of evolution of gas in steel. With a very mild steel containing 0·12 per cent. Carbon and 0·35 per cent. Manganese the evolution commenced at about 150°, the rate of evolution had a minimum value at about 200°, and a maximum at 400°. Between 500° and 600° a high maximum was obtained, falling to a minimum with the termination of the Ac_2 range. With the commencement of the Ac_3 range the evolution rose, then fell, and again continuously rose with further increase of temperature. Upon heating to 1,200°, a volume of gas equal to from eleven to twelve times that of the

* *Proceed. Royal Society*, 1867.
† *Iron and Steel Inst. Journ.*, 1880, p. 347.
‡ *Ibid.*, 1880, p. 181.
§ *Ibid.*, 1896, vol. ii., p. 161.
‖ *Ibid.*, 1903, vol. i., p. 371.
¶ *Comptes Rendus*, vol. cxlv., pp. 1280-1283.

steel was extracted. Up to 400°, the gas consisted almost entirely of CO_2, which disappears at 550°, above 400° H and CO, and above 550° a quantity of N, not more than 10 per cent. of the gas, was obtained.

The question as to the quantity and effect of Nitrogen in iron and steel has received considerable attention, and H. Braune * has given an exhaustive account of its occurrence and influence on the physical properties.

The following table shows the volume percentage of Nitrogen together with Hydrogen and Carbon Monoxide present in steel made by various processes :—

Nature of Specimen.	Nitrogen.	Hydrogen.	Carbon Monoxide.
Bessemer rail steel,	9·7	90·3	0·0
„ spring steel,	18·1	81·9	0·0
„ rail steel before introducing spiegel,	10·5	88·8	0·7
„ rail steel after addition of spiegel,	23·0	77·0	0·0
Steel before hammering,	5·9	92·0	1·4
„ after „	23·3	73·4	1·3
Open hearth steel,	30·8	67·0	2·2

Nitrogen may be present in the free state or combined, and it is interesting to note that there are two nitrides of iron known, Fe_4N_2 and Fe_5N_2, both these compounds, however, are decomposed at temperatures but slightly above their temperatures of formation—namely, 600° to 700°—at higher temperatures decomposition takes place more rapidly.

Many conflicting statements have been made with regard to the physical effect of Nitrogen on steel, some workers have claimed an increase in tensile strength as one of its effects, but most investigators look on Nitrogen as an extremely deleterious element, in view, however, of the discrepancies found in the various determination of Nitrogen, the conclusions at present put forward must be accepted with every reserve.

T. Baker † has also carried out a research on the nature and volume of the gases given off when steel is heated *in vacuo*, and on the part played by these gases in the production of blowholes.

Table lxxii. gives a summary of his results for a steel without blowholes and a steel of similar composition with blowholes. To prepare these specimens equal quantities of converted bar were melted in two crucibles in the same coke-fired furnace. To one was added a small quantity of Aluminium, and each was cast in a cast-iron mould 6 cubic centimetres. One of the ingots thus obtained was perfectly sound, whilst the other was full of blowholes. The following is the chemical analysis of the two specimens used :—

	Per cent.	Per cent.
Combined Carbon,	0·81	0·90
Silicon,	0·08	0·88
Manganese,	0·050	0·096
Aluminium,	—	0·033
Sulphur,	0·028	0·023
Phosphorus,	0·019	0·019

* *Bulletin de la Société de l'Industrie Minérale*, vol. vii., pp. 489-544.

† *Iron and Steel Inst.*, Carnegie Scholarship Memoirs, vol. i., 1909, p. 219.

TABLE LXXII.

Temperature of Extraction.	Steel without Blowholes. Volume in Cubic Centimetres.						Weight Taken, 69·31 Grammes. Composition.				
	Total.	CO_2.	H_2.	CO.	CH_4.	N_2.	CO_2.	H_2.	CO.	CH_4.	N_2.
Degrees C.							Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
519, . .	6·53	0·07	6·37	0·07	0·02	0·00	1·07	97·54	1·07	0·30	0·00
600, . .	10·67	0·19	8·44	2·00	0·07	0·00	1·78	79·10	18·74	0·65	0·00
672, . .	12·87	0·35	8·07	4·40	0·07	0·00	2·71	62·70	34·18	0·54	0·00
688, . .	22·91	0·75	6·96	15·02	0·12	0·03	3·27	30·38	65·56	0·52	0·13
719, . .	12·61	0·07	4·74	7·72	0·06	0·01	0·55	37·58	61·22	0·47	0·08
765, . .	6·71	0·02	3·35	3·26	0.05	0·02	0·29	49·92	48·58	0·74	0·29
802, . .	4·29	0·00	2·24	1·97	0·08	0·00	0·00	52·21	45·92	1·86	0·00
862, . .	4·59	0·05	2·24	2·22	0·08	0·00	1·08	48·80	48·36	1·74	0·00
936, . .	5·04	0·03	2·53	2·42	0·07	0·00	0·59	50·19	48·01	1·38	0·00
979, . .	5·64	0·01	2·83	2·75	0·04	0·01	0·17	50·17	48·75	0·70	0·17
Total, .	91·86	1·54	47·77	41·83	0·66	0·07	..	..	..	..	..
	Steel with Blowholes.						Weight Taken, 63·261 Grammes.				
530, . .	3·28	0·09	3·04	0·06	0·05	0·04	2·74	92·68	1·82	1·52	1·22
603, . .	2·96	0·06	2·70	0·08	0·06	0·06	2·02	91·21	2·70	2·02	2·02
681, . .	4·36	0·06	2·16	2·01	0·15	0·03	1·37	48·39	46·10	3·45	0·69
696, . .	5·45	0·02	1·49	3·85	0·05	0·04	0·36	27·34	70·64	0·91	0·73
720, . .	5·04	0·03	1·84	3·11	0·06	0·00	0·59	36·50	61·70	1·19	0·00
762, . .	3·80	0·02	1·87	1·81	0·09	0·01	0·52	49·21	47·63	2·37	0·26
825, . .	3·98	0·02	2·01	1·87	0·07	0·01	0·50	50·50	46·98	1·75	0·25
893, . .	4·24	0·03	2·18	1·93	0·10	0·00	0·71	51·41	45·51	2·35	0·00
944, . .	4·48	0·02	2·32	2·08	0·05	0·01	0·45	51·78	46·42	1·11	0·22
1,016, . .	4·50	0·02	3·38	1·05	0·05	0·00	0·44	75·11	23·33	1·11	0·00
Total, .	42·09	0·37	22·99	17·85	0·73	0·20	..	..	..	..	..

The extraction of the gas was continued over ten days, the period of heating being eleven hours per day; at the end of each day the gas was collected and analysed. In the case of the unsound pieces, as many as possible of the blowholes were cut open to allow the contained gases to escape, as it was desired to obtain the gases from the solid portion of the steel. On comparing the results, it will be seen that the total volume given off from the *sound* steel was 91·86 cubic centimetres, equal to 10·4 times the volume of the steel employed, whilst from the *unsound* piece the total volume evolved was 42·09 cubic centimetres, equal to 5·2 times the volume of the specimen. It is also seen that the maximum evolution of gas occurs at temperatures which coincide with the $Ar_{1\text{-}2\text{-}3}$ point for both steels. The commonly accepted hypothesis that the effect of Aluminium in preventing blowholes is due to the fact that it increases the solubility of the gas in the solid metal seems to be confirmed by the above results.

There is practically no conclusive evidence as to the influence of these various gases on the physical properties of steel, apart from the mechanical defects, such as blowholes, produced by their presence; and so

far all attempts to trace any connection between the presence of occluded gases and the strength, ductility, &c., of the steel have failed. It is a well-known fact that pickling often produces a curious brittleness in steel wire, or cold drawn steel tubes, which is completely removed by annealing. This brittleness has been attributed to the absorption of large volumes of nascent Hydrogen, which is again evolved during annealing, and the steel is restored to its ductile condition.

The part played by gases in the production of blowholes in steel is a question of the greatest interest and importance to the steel manufacturer, as when present to an excessive extent they produce unsound ingots which roll into defective finished material. In some cases of what are known as "wild heats," a few seconds after the ingot has been cast, a sudden evolution of gas will cause the whole of the metal to boil over, leaving little more than a shell in the mould. A sudden evolution of gas in this way may be due either to the solvent power of the steel being suddenly reduced owing to alteration in the temperature, or to some chemical action between the steel itself and the various impurities it contains, giving rise to the sudden generation of gas. When steel behaves in this way it will generally be found that, whatever may be the immediate cause of the evolution of the gas, the primary cause is over-oxidation or too high a casting temperature. Thus Bessemer charges very high in Silicon, which blow extremely hot, are liable to become surcharged with Oxygen, which the Ferro-Manganese and Spiegel do not completely remove, and frequently "wild heats" result.

The sudden evolution of the gas in the moulds seems probably to be due to two causes:—(1) By the reduction of the temperature the solvent power of the steel for the gases is lowered, and consequently certain proportions of the gas are liberated; this may apply to the Hydrogen, Nitrogen, and the Carbon Monoxide. (2) An evolution of CO or CO_2 due to chemical action. It has been pointed out, in dealing with thermochemistry, that certain chemical reactions take place only within a given range of temperature. It is conceivable that, in the case of a very "hot blow," the critical temperature at which Carbide of Manganese and Metallic Manganese are able to reduce Oxide of Iron is exceeded, and consequently the reaction takes place only to a limited extent, until the temperature of the metal is reduced by being cast into the cold mould. This would, to a large extent, explain the sudden evolution of gas which sometimes takes place in ingot moulds, and which it is difficult to explain alone on the hypothesis of gases being liberated from solution.

In good practice the wild heats referred to are comparatively rare, and the blowholes in ingots, although always present, can, by suitable additions of Ferro-Silicon and Aluminium, be so reduced that sound finished material may be relied upon. Even the soundest ingots, if broken through, will be found to contain numbers of blowholes, but as these are generally quite bright and free from oxide, in the majority of cases, they either weld up or are reduced to such a minute size, during the process of rolling or forging, that they are not a source of danger in the finished steel. If this were not so in steel which has been carefully manufactured, the production of sound tubes of thin gauge would be impossible. Sometimes, however, these blowholes are of such a size that they do not close up, and the author is aware of a case of a shaft, 15 inches in diameter, which broke owing to a blowhole 2 inches long, notwithstanding that the shaft had been forged from a very large ingot. In other cases the surface of the holes is coated with a thin film of oxide, which prevents the perfect welding, and consequently may lead to serious defects in the material when rolled.

Oxygen exists in steel in the form of Oxide; and Law* has recently shown the great influence this has on the physical properties of the steel, especially in the case of tin plates. He described the appearance of Oxide of Iron under the microscope as consisting of minute black specks distributed throughout the mass of the metal. These can only be seen if the specimen has received a perfect polish and requires a magnification of at least 1,000 diameters; besides these Oxide patches, a certain amount of Oxide exists in solution in the iron.

In a number of determinations, the Oxygen was found to vary from 0·021 per cent. in good steels to 0·046 in bad steels; these quantities seem extremely small, but it must be remembered that 0·046 per cent. of Oxygen corresponds to 0·2 per cent. of Ferrous Oxide, which is an appreciable amount of impurity for steels. It is interesting to note that Oxide of iron, when present in steel, has a powerful influence on its liability to corrosion, increasing this to a considerable extent.

Prevention of Blowholes.—The well-known fact that small additions of Silicon and Aluminium largely prevent these blowholes has been explained in two ways—(1) by increasing the solvent power of the steel for the gases and (2) by the removal of the Oxide of Iron and oxidising gases by the oxidation of the Silicon and Aluminium. Probably they act in both ways, as it is clear that Silicon and Aluminium could not remove the Hydrogen or Nitrogen by chemical combination, and hence, so far as these gases are concerned, the first explanation is probably largely correct; but with regard to occluded Oxygen or CO, and Oxide of Iron, it is probable these are largely removed by the reducing action of the Silicon or Aluminium. Further, when metal containing any appreciable amount of Carbon cools down, it is possible that the Carbon may reduce some of the Oxide of Iron present with formation of CO, and if the Oxide of Iron is first removed by Aluminium this reaction cannot take place. Aluminium acts more effectively than Silicon in this way, and this is explained by the greater affinity of Aluminium for Oxygen.

Pipes and Cracks in Ingots.—The piping of ingots is not caused by gases in the metal, but is due to shrinkage caused by contraction. The metal at the bottom and sides in contact with the mould is cooled first, and as it contracts the fluid metal in the centre and top tends to act as a feeder, with the result that a cavity is left in the top of the ingot. The position of the cavity will depend upon the regular cooling of the ingot; if cooled equally on all sides; the metal on contraction, acting under gravity, will sink and leave a central hollow near the top. As steel ingots are generally chilled on their top surfaces, the upper end of the pipe may be some little distance from the top of the ingot. If the ingot is laid down in the horizontal position before it has completely set, the cavity, instead of being confined to the top part, will be more or less distributed throughout the entire length, and this is one reason why it is important to heat large ingots in the vertical position, as in soaking pits, rather than in horizontal reheating furnaces. Again, if ingots are cooled unequally from any cause, the pipe, instead of being central, may be more or less on one side of the top of the ingot.

The cracks in ingots which arise from unequal contraction of the ingot in the moulds, may be either longitudinal or transverse. If through careless teeming, or any irregularity in the surface of the mould, the molten steel "seizes on" at different levels, this will probably produce transverse cracks, as the ingot itself is contracting and the mould is expanding, and hence the tendency is to tear the surface. If the exterior or shell of

* *Iron and Steel Inst. Journ.*, 1907, vol. ii., p. 98.

the ingot is also cooled much more rapidly than the interior, the rapid contraction of the steel is liable to cause cracks on the surface. As rapid cooling of the outside of an ingot may be the cause of cracks, so if a cold ingot is placed in a hot furnace the rapid expansion of the exterior compared to the interior may cause internal cracks, and in some cases ingots will split quite in two from this cause. It is therefore desirable, whenever possible, to charge the ingots while hot into the furnace, or, in cases where it is necessary to charge them cold, the furnace should be at as low a temperature as possible, and be gradually heated up; this is especially important with high Carbon steel.

CHAPTER XVII.

SPECIAL STEELS OR STEEL ALLOYS.

HITHERTO we have considered steel as consisting amost entirely of iron combined with more or less Carbon, and containing a certain proportion of Manganese. We will now consider shortly the properties of certain special steels, that is of steels which result from mixing with iron other metals with or without Carbon.

Iron alloys readily with most metals, so that the number of steels of this nature which can be produced is necessarily large, moreover it has been found that in many cases a comparatively small difference in the proportion of the added metal makes a very considerable difference in the properties of the resulting special steel. Hence it is easy to see that the field is a very large one, and one that has not yet been fully developed.

In the following pages we shall deal only with the better known of these alloys, some of which are already of the very greatest commercial importance, and with others which are evidently destined to become so as our methods of manufacturing them improve.

The metals which chiefly influence the properties of steel, when admixed with it, may be arranged in a descending scale, as follows:—Manganese, Nickel, Chromium, Titanium, Tungsten, Aluminium, Vanadium, Boron, Uranium, Copper, Tin, Zinc, Bismuth, Lead. Other metals, such as those of the Cerium group, the heavy Platinum metals, &c., doubtless have a very marked effect upon steel when properly introduced into it, but in most cases the field is at present entirely unexplored, or the cost of the added metal renders the resulting alloy too expensive for commercial use.

In this chapter we have taken the alloys formed by steel with other metals in alphabetical order as being most convenient for reference. Copper, tin, zinc, bismuth, and lead are dealt with in the chapter on "Influence of Metals and Metalloids on Steel," as they are never purposely added, but only occur accidentally as impurities.

Aluminium is usually added to steel, not with the object of forming any alloy, but because of the specific action which the metal has been found to exert on molten cast steel. All steel when in a molten state may be considered to be more or less oxidised, and to contain a greater or less amount of dissolved Iron Oxide, which diminishes both its fluidity and its strength. As this oxidised metal cools, the Oxide, under the action of Carbon, is partially reduced, giving rise to the formation of Carbon

Monoxide gas. The gas so evolved causes a more or less violent ebullition in the molten metal, giving rise to unsound ingots containing the well-known "blowholes." The addition of very small amounts of metallic Aluminium to such metal is found to greatly facilitate the flow of the molten metal from the ladle, to stop the violent evolution of gas, and to allow of the production of sound ingots without blowholes. The explanation of this action appears to be that Aluminium has a far greater affinity for Oxygen at high temperatures than iron has, the Iron Oxide being consequently reduced, while the Alumina formed passes out of the metal as slag.

A small addition of Aluminium is found to stop, not only the evolution of Carbon Monoxide from molten steel, but also the evolution of other occluded gases, Nitrogen and Hydrogen. The cause of this action is a little uncertain, but it is supposed that the de-oxidation of the molten metal increases its power of retaining occluded gases, and that when the Iron Oxide is reduced by the addition of the Aluminium, the metal is able to retain in solution gases that would otherwise be expelled.

Aluminium is almost always added to the metal when it is being tapped from the furnace or converter, and is usually thrown into the ladle. The amount added is small, in the case of open hearth steel from 2 to 5 ozs. per ton, and in the case of Bessemer steel some 6 to 8 ozs. When Aluminium has been added the surface of the ingot or casting is found to be smoother.

Aluminium steel has been thoroughly investigated by Mr. Hadfield, to whose indefatigable labours we are so largely indebted for our knowledge of the alloys of steel with other metals. The student will do well to consult his original paper read before the Iron and Steel Institute in 1890.* According to this investigator it is doubtful whether Aluminium increases the fluidity of properly made steel. If it does indeed do so the increased fluidity is probably not due to real lowering of the melting point, but to the removal of the Oxide of Iron.

Aluminium above about ·5 per cent. causes the metal to become quite thick and "creamy" and to set quickly, an effect probably due largely to the entanglement of Alumina in the metal as slag.

Hadfield's results show that up to about ·85 per cent. Aluminium, the *cast* annealed samples bent double, cold; unannealed tests did not give so good a result. Increased percentages of Aluminium distinctly reduced the toughness, both in the annealed and unannealed samples. With two exceptions all specimens were sound but not more so than Silicon steel of corresponding percentages.

As might be expected from the soft nature of the metal, its addition to iron does not materially affect the hardness, resembling in this respect the effect of Silicon. As regards *fracture*, Aluminium in the case of cast specimens opens the grain—*i.e.*, increases the size and coarseness of the crystals. In 5 per cent. alloys and upwards the crystals become very large, and cleave somewhat after the nature of Spiegeleisen.

The forged specimens of Aluminium steel, prepared by Mr. Hadfield gave the following results:—

As much as 5·6 per cent. Aluminium may be present before malleability practically ceases: about the same limit as was also found in the case of Silicon steels. The specimens examined were low in Manganese. In Table lxxiii. will be found the chief results obtained from the specimens examined, and in Table lxxiv. the same compared with similar specimens of Silicon steel. It will be seen that up to 2·24 per cent. the annealed samples *bend* double cold, but upon reaching 5 per cent. a great diminution of strength takes place, and annealing practically produces no effect. The *tensile strength* is

* *Iron and Steel Inst. Journ.*, 1890, vol. ii., p. 161.

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TABLE LXXIII.—ALUMINIUM STEEL—HADFIELD'S RESULTS.

TENSILE TESTS OF ANNEALED AND UNANNEALED BARS; ALSO SPECIFIC GRAVITY, FORGING, WELDING, AND BENDING TESTS.

ANALYSIS PER CENT.								Specific Gravity.	Drillings taken from	How Ingot Forged.	Whether Tested in Annealed or Unannealed Condition.	Original Diameter in Inches.	Original Area in Inches.	Limit of Elasticity in Tons per Sq. Inch.	Amount of Stretch in Inches at Elastic Limit.	Breaking Load in Tons per Sq. Inch on Original Area.	Length in Inches on which Extension Measured.	Total Extension per cent.	Reduction of Area per cent.	Appearance of Fracture of Test Bar.	Appearance of Fracture of Annealed Forged Bar from which Test Bar was Prepared.	Bending Tests of Annealed Forged Bars 1½ inch wide by ½ inch thick.	Welding Test.	REMARKS.
Carbon	Silicon.	Sulphur.	Phosphorus.	Manganese.	Aluminium.	Calculated Percentage of Aluminium.	Loss (Approx.) per cent. of Aluminium.																	
·22	·09	...	...	·07	·15	·25	·10	...	Ingot.	Very well.	Unannealed.	·7979	·50	21·00	...	29·00	2	36·70	62·90	Granular; very dark; a little roaked; smooth on outside.				1. These tests were made with a Whitworth machine.
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	20·00	...	25·00	2	41·30	63·82	Dark granular; a little roaked; smooth on outside.	Close fine granular.	Bent double cold.		
·15	·18	·10	·04	·18	·38	·50	·12	...	Ingot.	Fairly well.	Unannealed.	·7979	·50	23·00	...	30·00	2	37·85	58·18	Dark granular.				
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	20·00	...	26·00	2	40·35	60·74	Dark granular; smooth on outside.	,, ,,	,, ,,		
·20	·12	...	...	·11	·61	·75	·14	7·781	Ingot.	Rather shelly.	Unannealed.	·7979	·50	21·50	...	28·00	2	38·40	54·50	Dark granular; several specks in body.			Would not weld.	
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	18·00	...	25·50	2	40·00	61·98	Dark granular; rough on outside.	Fine close granular; much closer before annealing.	,, ,,		
·18	·16	·09	·03	·14	·66	1·00	·34	...	Ingot.	Very well.	Unannealed.	·7979	·50	20·50	...	29·00	2	33·35	49·86	Dark granular; several long specks in body.				
...	...	...	...	...	...	...	...	...	...	...	Annealed	·7979	·50	18·00	...	27·00	2	33·00	52·14	Dark granular; rough on outside.	Fine grain.	,, ,,		
·17	·10	...	...	·18	·72	1·25	·53	7·755	Ingot.	Very well.	Unannealed.	·7979	·50	22·00	...	28·00	2	40·00	60·74	Dark granular.			,,	
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	18·00	...	25·00	2	47·10	64·86	Dark granular; smooth on outside.	Fine close grain; much closer before annealing.	,, ,,		
·26	·15	·08	·04	·11	1·16	1·50	·34	...	Ingot.	Very well.	Unannealed.	·7979	·50	23·00	...	33·00	2	32·05	51·46	Dark fine granular; smooth on outside.				
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	21·00	...	29·00	2	34·40	53·02	Dark granular; smooth on outside.	Fine grain.	,, ,,		
·21	·18	...	...	·18	1·60	2·00	·40	7·6237	Ingot.	Rather shelly.	Unannealed.	·7979	·50	20·00	...	31·00	2	32·70	52·14	Dark granular; rough on outside.				
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	13·00	...	26·00	2	36·35	67·06	Dark granular; rough on outside.	Coarser.	,, ,,		
21	·18	·09	·03	·18	2·20	2·50	·30	...	Ingot.	Fairly sound.	Unannealed.	·7979	·50	21·00	·0080	31·00	2	22·75	27·80	Crystalline; rather coarse.			,,	
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	19·00	·0095	28·00	2	34·87	47·12	Dark granular; fibrous; very rough on outside.	,,	,, ,,		
·24	·18	...	...	·32	2·24	3·50	1·26	7·554	Ingot.	Fairly well.	Unannealed.	·7979	·50	21·50	·0085	32·50	2	20·67	24·64	80 per cent. outer circle, crystalline; 20 per cent. inner circle, finer crystalline; rather coarse.				
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	18·50	·0133	28·50	2	33·02	48·62	Dark granular; fibrous.	,,	,, ,,		
·22	·20	·08	·03	·22	5·60	6·00	·40	...	Ingot.	Very shelly.	Unannealed.	·7979	·50	None visible.	...	38·00	2	3·67	3·96	Crystalline; lustrous; broke in radius.				
...	...	...	...	...	...	...	...	...	...	...	Annealed.	·7979	·50	27·00	·0050	36·00	2	6·45	6·16	Crystalline; lustrous; broke in radius.	Coarse.	16° Broken.		
·26	·33	·08	·03	·25	9·14	10·00	·86	6·6726	Ingot.	No test; bar made would not forge														

found not to be increased so much by Aluminium as by Silicon. The increase in the *elasticity* is slight, if any, and it will be seen from Table lxxiv. that Aluminium does not raise the elastic limit so much as Silicon. Generally, Aluminium and Silicon are found to *stiffen* iron but little (as might be expected from their properties), whilst Carbon, Chromium, Tungsten, Manganese, and Nickel increase *rigidity*, as their properties might also lead us to expect. *Hardness* also is not increased in the forged state, any more than in the cast. Forged material containing 5 per cent. Aluminium is very soft, and easily drilled or filed. The action of Aluminium may, therefore, be classed along with that of Silicon, Sulphur, Phosphorus, Arsenic, and Copper as giving no increase of hardness to iron, in contradistinction to Carbon, Manganese, Chromium, Tungsten, and Nickel. Water quenching upon either forged or cast Aluminium steel (in which Carbon is practically absent) seems to produce no effect, the samples when dipped, at even a welding heat, being almost unchanged. When Carbon is present the ordinary hardening action occurs. The *welding properties* of the Aluminium specimens examined (from ·61 to 2·2 per cent. Aluminium) were very poor.

Aluminium, like Silicon, appears to cause a precipitation of Graphite—thus Hadfield found when adding between 3 and 4 per cent. of Aluminium to ordinary Spiegel, that the well-known Spiegel fracture was entirely changed to one resembling ordinary close No. 3 grey pig iron.

TABLE LXXIV.—Comparative Table of Forged Silicon and Aluminium Steel, both Materials having been Annealed.

	C.	Si.	Al.	Limit of Elasticity.		Ultimate Stress Tensile Strength.		Extension per cent. on 2″.	Reduction of Area p. cent.	Bending Tests of Annealed Forged Bars.
	Per cent.	Per cent.	Per cent.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.			
Si, Steel A,	·14	·24	...	15·17	34,000	25·0	56,000	37·55	60·74	Bent double cold.
Al, ,, ,,	·15	...	·38	20·0	45,800	26·0	58,246	40·35	60·74	,,
Si, ,, B,	·18	·73	...	19·0	42,560	29·5	66,024	34·02	52·66	,,
Al, ,, C,	·18	...	·66	18·0	40,300	27·0	60,470	33·0	52·14	,,
Si, ,, ,,	·19	1·60	...	25·0	56,000	33·0	74,100	35·0	54·52	,,
Al, ,, F,	·21	...	1·60	13·0	29,100	26·0	58,246	36·35	67·0	,,
Si, ,, D,	·20	2·18	...	25·5	57,120	34·0	76,200	36·50	59·96	,,
Al, ,, H,	·24	...	2·24	18·5	41,440	28·5	62,800	33·0	48·02	,,
Si, ,, ,,	·26	5·53	...	29·0	64,960	39·0	87,400	0·70	2 00	Would not bend.
Al, ,, I,	·22	...	5·60	27·0	60,470	36·0	80,600	6·45	6·16	16° broken.

As regards the application of Aluminium for alloying with steel, Mr. Hadfield considers that it may find a use for certain special purposes with higher Carbon steels, where Silicon does not seem to act so powerfully in producing soundness as in the case of milder steels with Carbon ·5 per cent. and under. Its special advantages seem to be that it combines in itself the advantages of Silicon and to some extent of Manganese, but as long as alloys containing these elements are so cheap, its extensive use seems hardly probable.

Boron Steel.—Boron in steel seems to have rather interesting properties, although it is doubtful whether any commercial value will ever be attached to the alloys. Messrs. Moissan & Charpy prepared an alloy, of which they give the following analysis :—

Boron,	0·58 per cent.
Carbon,	0·17 ,,
Manganese,	0·03 ,,

Traces of Silicon, Phosphorus, and Sulphur.

This material could be rolled out in the form of a cylindrical bar, and could be readily forged at a dull red heat, but crumbled under the hammer when heated too strongly. With such a steel there is a very marked critical point at 1,140° C., equal in intensity to that corresponding with the point of recalescence of hard steel. A rolled and annealed Boron steel which gave a tensile strength of 46 kilos. per square mm. and 11 per cent. extension, gave, after hardening by heating to 1,100° C., and quenching, a tensile strength of 129·5 kilos. per square mm., with an extension of only 3 per cent. As regards its increase of strength by quenching, therefore, Boron steel behaves like high Carbon steel, whilst the diminution of extension is less marked than with the latter. It is remarkable that the hardness of Boron steel (as distinct from its tensile stress) increases but little on heating and quenching. Thus it was found that test pieces having a tensile strength of from 120 to 137 kilos. per square mm. could be filed as easily as those which had not been heated and quenched. This differentiates the action of Boron from that of Carbon in steel on heating and quenching, as the action of Boron seems only to increase the tensile strength without actually hardening the metal.

Chromium.—Chromium is now used to a fairly large extent in the manufacture of steel, both for special qualities and for the production of tires and axles. Chromium is usually employed in the form of Ferro-chromium, which is now a regular article of commerce, and can be obtained of varying percentages of Chromium up to as high as 70 per cent. A refined Ferro-chromium is also on the market, containing 65 to 70 per cent. of Chromium, with only from ·5 to 1 per cent. Carbon. The material is specially useful for high-class tool steel. A still richer product is manufactured containing from 96 to 98 per cent. Chromium, 2 to 3 per cent. iron, ·75 to 1·25 per cent. Carbon, and ·05 to ·75 per cent. Silicon. Chrome iron ore is the most abundant source of the metal, and is found in the Shetland Isles, in Banffshire, &c.; in the Department of Var, France, Silesia and Bohemia, Greece, Asia Minor, the Ural Mountains, and in New Caledonia; deposits also occur in the United States and in New South Wales.

Ferro-Chromium as made in the blast furnace requires a very large consumption of fuel for its production, about 3 tons of coke per ton of alloy of 40 per cent. Chromium. It is usually very high in combined Carbon, even more so than rich Ferro-manganese, and, unlike the latter, is apt to contain Sulphur, unless special precautions are taken.

The effect of Chromium on steel may be briefly summed up as follows. It does not confer *soundness* on steel, in this respect differing from both Silicon and Aluminium. In small quantities it slightly raises the *tensile strength* of steel without seriously diminishing ductility; when added in too large quantities it induces *brittleness;* both of these effects, however, are modified by the percentage of Carbon present. Hadfield has shown that up to a certain percentage, say ·75, or even 1 per cent., Chromium does not materially affect the product, whether as regards *yield point, tensile strength, hardness test* (Turner's), or hardening qualities by water quenching. Chromium does not materially harden iron, and, in the absence of Carbon, its addition up to 3 or 4 per cent. does not produce any greater hardness than do similar Silicon and Aluminium additions. Carbonless, or nearly Carbonless, Chrome steel does not harden when water quenched.

There was a remarkable series of Chrome steels exhibited by MM. J. Holtzer & Cie. at the last Paris Exhibition. The mechanical properties of these steels are shown in the following table, the Carbon being constant at about ·4 per cent. :—

Chromium.	Condition.	Elastic Limit.		Ultimate Stress.		Elongation.	Contraction.*
Per cent.		Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.	Per cent.	
5	Annealed,	17·8	39,872	31·8	53,760	24·0	0·240
	Hardened and tempered,	48·8	109,312	55·2	123,648	12·0	0·370
10	Annealed,	22·9	51,296	42·0	94,080	21·5	0·440
	Hardened and tempered,	42·4	94,976	54·3	121,632	12·0	0·536
15	Annealed,	25·4	56,896	45·3	101,472	18·5	0·500
	Hardened and tempered,	48·8	109,312	58·1	130,144	11·5	0·546
20	Annealed,	21·2	47,488	36·1	80,864	21·5	0·465
	Hardened and tempered,	27·6	61,824	40·3	90,272	19·5	0·515
25	Annealed,	29·8	66,752	42·2	94,526	18·0	0·621
	Hardened,	27·6	61,824	40·4	90,496	20·0	0·500
30	Annealed,	31·8	71,232	41·6	93,184	19·0	0·620
	Hardened,	28·8	64,518	39·0	87,360	19·0	0·650

The length on which the elongation was measured is not stated, but probably 2 inches.

Chrome steel has been largely used in the manufacture of steel tires and springs for railway purposes, many of the springs used on locomotives and tenders on the North-Western Railway being of this material. For armour plates, also, the material is being largely used, and for armour piercing projectiles. Chromium has also been used in combination with Nickel in steel, forming a material combining the advantages of Chrome steel and Nickel steel.

Steel containing from ·9 to 1 per cent. combined Carbon and 2 to 2·75 per cent. Chromium, the other constituents being normal, is found to give a satisfactory material for armour-piercing projectiles; but this material, in the form of a shell, requires, like all other special steels for this purpose, very careful treatment in the "hardening" and "tempering" processes to bring the shells into a fit condition for satisfactory penetration.

Chromium is also occasionally added to steel in the manufacture of special brands of file steel, an approximate composition of which would be:—

Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Combined **C**, 1·20	**Si**, 0·08	**Mn**, 0·35	**Cr**, 3·0	**S**, 0·027	**P**, 0·045	**Fe**, 95·298

Steel of the above composition, and which may be made satisfactorily in the "open hearth" or Siemens furnace, is cast without difficulty into sound ingots.† The ingot moulds used for Chrome steel must be in good condition, free from surface cracks, and the stream of steel must be teemed most carefully into the ingot moulds, which should be cast preferably from the bottom to ensure a clean smooth skin on the surface of the ingot, otherwise considerable trouble is likely to arise in the subsequent "cogging" and rolling due to seams or "roaks," which would render a bar useless for the purpose of files. In the heating of these ingots care, too, must be taken to bring them up slowly and

* Ratio of fractured to original section.

† The charge is worked as for other high Carbon steels, and the Chromium introduced as Ferro-Chromium towards the end of the operation, care being taken, when the addition is made, that the slag is in good working order and not in a strongly oxidising condition.

as uniformly as possible to a red heat, and while soaking them thoroughly to avoid burning them.

Manganese.—Manganese is chiefly known to us in the form of Ferro-manganese, a triple compound of Iron, Manganese, and Carbon, in which the Manganese may be present up to 85 per cent.

Manganese may be said to be universally present in commercial steel made by the Bessemer or open hearth processes of manufacture. As has been described in the foregoing pages, it is usually added to the fluid steel in the ladle after tapping, or in the converter itself just prior to casting into the ladle. A great part of the Manganese so added is found subsequently as Oxide of Manganese in the slag, but a part always remains in the metal, and, ordinarily, steel contains in the finished state from ·3 to 1 per cent. of Manganese. The presence of this Manganese seems necessary to counteract the tendency to red shortness, which all steel melted in the presence of iron oxides or air otherwise possesses.

We are chiefly indebted to Hadfield for our knowledge of the properties of Manganese steel—that is, steel containing a fairly high percentage of Manganese as distinct from the small amount present in ordinary steel. Before his investigations it was generally believed that steel became brittle and comparatively worthless when the Manganese exceeded 2·75 per cent., and Hadfield found that when the Manganese present was increased to over 7 per cent. the result was, for all practical purposes, a new metal, and one which has since become of great value. With from 2·75 to 7 per cent. of Manganese the alloy is brittle, but when the proportion is increased to more than 7 and from this minimum up to about 20 per cent. the result is a metal possessing extraordinary strength and toughness. In ordinary steel it is found that as soon as the Manganese exceeds the usual limits of about ·5 per cent. for mild steel, the tensile strength increases rapidly, the elongation not decreasing so much in proportion as usually occurs in hard Carbon steel. When less than ·2 per cent. Manganese is added to decarburised iron it is very difficult to roll or forge the ingots, but above this they become malleable. Mild steel containing only ·2 per cent. Manganese is usually unsound and rises in the ingot moulds, the honeycombs, however, closing up more or less on the material being forged, rolled, or otherwise reduced. As the proportion of Manganese increases, the material becomes sounder, but on exceeding 1 per cent. the presence of Manganese begins to be detrimental, the elongation is much reduced, and, in the case of steel castings, they become difficult to anneal. As before stated, the maximum amount which may be present in low-percentage Manganese steel before the steel becomes absolutely brittle and rotten seems to be about 2·5 per cent.

In the cast state Manganese steel, with from 2·5 to 7·5 per cent. Manganese, is extremely brittle, so much so that it can be compared to glass in this respect. The extreme point of brittleness seems to occur at 4 to 5 per cent.; after this a slight increase of strength takes place, but even with about 6·5 per cent. it will only stand the same transverse test as cast iron. The Carbon in these brittle samples is only from ·3 to ·5 per cent. It has been noticed that the more purely the alloy consists of iron and Manganese the more brittle the product becomes. It is extremely hard, approaching dead-hardened steel, and no tool of any kind will touch it. Although so brittle in its cast state, a considerable increase in its strength takes place when hammered or forged, but it is still comparatively brittle and commercially useless.

Above 7·5 per cent. of Manganese, brittleness and extreme hardness begin to disappear, and with forged steel of higher percentages of Manganese, a metal possessing great hardness, and a very considerable elongation is

obtained. Thus, Hadfield gives particulars of a specimen of forged material containing 13·75 per cent. of Manganese and ·85 per cent. of Carbon, which, when water-toughened, had a *tensile strength* of 65 tons per square inch with nearly 51 per cent. *elongation*, and another specimen with 69 tons *tensile strength* and 46 per cent. *elongation*. This has been used for tools, such as axes and razors, with very good results. This alloy with about 13 per cent. of Manganese and 1 per cent. of Carbon is the usual composition of the well-known Hadfield steel.

All these Manganese alloys possess very peculiar hardness both in the cast and forged state, and it is scarcely possible to machine them in ordinary practice; the hardness varies considerable, being greatest in cast state with 5 to 6 per cent. of Manganese and ·3 to ·5 per cent. of Carbon, and gradually decreasing until 10 per cent. of Manganese is reached, which is the softest alloy. The hardness then increases up to 22 per cent. of Manganese, after which the material has more the properties of cast iron, about 2 per cent. of Carbon being present, which obscures the action of the Manganese.

The following table (lxxv.)* gives some of Hadfield's results of the mechanical tests of forged Manganese steels, containing from ·83 to 21·69 per cent. of Manganese.

Manganese steel may be considered for practical purposes wholly *unmagnetisable*.

Steel containing about 1 per cent. of combined Carbon and 14 per cent. of Manganese, is stated to have an electrical resistance thirty times that of copper, and eight times that of wrought iron.

The following figures give the result of analysis made on drillings taken from a cast-steel wheel:—

Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Combined **C**, 1·150;	**Si**, 0·551;	**Mn**, 13·733;	**S**, 0·043;	**P**, 0·091.

This steel was found to be feebly magnetic. It was brittle to shock, and comparatively easily broken by a hammer, but exceedingly hard to drill. It is not improbable that had the Silicon and Phosphorus been present in less quantities, the steel would have been stronger to resist shock.

This Manganese steel possesses the peculiar advantage of being softened and toughened by the following treatment:—A piece heated to about 990° to 1,090° C., on being plunged at this temperature into cold water, becomes sufficiently soft to be easily filed, planed, or otherwise machined. The nearer the above temperatures are approached and the colder the water the tougher will be the material. Hardness is then restored by reheating to a bright red and cooling in air.

The use of Manganese steel is limited by the extreme difficulty experienced in machining it. For alloys from about 12 to 18 per cent. Manganese a great increase of *strength* and *ductility* is obtained by reheating nearly to whiteness and sudden cooling, both the *tensile strength* and *elongation* being improved. With large forgings the improvement brought about by quenching is naturally somewhat counterbalanced by the tendency to crack, caused by internal stresses. Heating and quenching, whilst increasing the tensile strength and elongation, have been found to lower the elastic limit.

Molybdenum.—Molybdenum steels are very similar to Tungsten steels in mechanical properties; Molybdenum, however, is said to be two or three times as powerful as Tungsten in its effect. Giesen † found that Molybdenum

* *Min. Proc. Inst. Civil Engineers*, vol. xcii.

† *Iron and Steel Inst.* Carnegie Scholarship Memoirs, vol. i., 1909, p. 31.

TABLE LXXV.—HADFIELD'S TESTS OF FORGED MANGANESE STEEL CONTAINING FROM ·83 TO 21·69 PER CENT. MANGANESE.

Mark.	Analysis. Per cent.			Tested in Natural State Specimens, D.			Air-toughened Specimens, C.			Oil-toughened Specimens, A.			Water-toughened Specimens, B.			Remarks.
	C.	Si.	Mn.	Maximum Stress.		Elongation.	Maximum Stress.		Elongation.	Maximum Stress.		Elongation.	Maximum Stress.		Elongation.	
				Tons per sq. in.	Lbs. per sq. in.	Per cent. in 8 ins.	Tons per sq. in.	Lbs. per sq. in.	Per cent. in 8 ins.	Tons per sq. in.	Lbs. per sq. in.	Per cent. in 8 ins.	Tons per sq. in.	Lbs. per sq. in.	Per cent. in 8 ins.	
498,	0·20	0·03	0·83	33	73,900	31	..	..	..	..	..	..	..	..	..	Reduction in area 46 per cent.
41,	0·40	0·15	2·30	56	125,500	6	..	..	..	..	..	..	..	..	..	" " 7 "
36,	0·40	0·09	3·89	33	85,400	1	..	..	..	..	..	..	..	..	..	
4,	0·52	0·37	6·95	25	56,000	2	21	47,000	2	19	42,500	2	23	51,500	2	
5,	0·47	0·44	7·22	27	60,500	2	27	60,500	5	25	56,000	3	25	56,000	2	
3,	..	..	7·50	39	87,400	4	..	..	..	..	..	..	..	..	..	" " 9 "
7,	0·50	0·28	7·90	..	..	..	28	62,700	8	30	67,900	7	..	..	..	
15,	1·00	0·42	9·15	..	..	..	..	..	..	42	94,000	17	..	..	..	
9,	..	..	9·20	40	89,600	6	..	..	..	..	..	..	..	..	..	" " 10 "
6,	0·61	0·30	9·37	33	73,900	5	38	85,400	16	38	85,400	15	39	87,400	15	
11,	0·95	0·21	10·11	38	85,400	5	39	87,400	14	41	91,800	20	..	..	..	
13,	0·85	0·28	10·60	34	76,200	4	41	91,800	17	42	94,100	19	40	89,600	17	
521-6 (lowest), 521 (average), 521-10 (highest),	0·72	0·37	10·83	..	..	..	..	..	..	..	..	..	46 50 53	103,000 112,000 118,800	22 25 29	Lowest, highest, and average result given of twelve different tests.
547-1u,	..	..	..	39	87,400	4	..	..	..	..	..	..	..	..	..	
547-7u, 547-16, 547-17,	0·85	0·37	12·29	..	..	..	..	..	..	..	..	..	63 64 65	141,100 143,400 145,000	45 45 50	Reduction in area 8 per cent. Water-toughened specimens average from 30 to 40 per cent.
26,	1·10	0·16	12·60	39	87,400	2	37	82,900	11	50	112,000	28	54	121,000	27	
26·0s,	..	..	12·70	47	105,300	6	..	..	..	..	..	..	..	..	..	
19,	0·92	0·42	12·81	39	87,400	5	48	107,500	20	58	129,900	32	61	136,600	37	
552-1,	0·85	0·23	13·75	..	..	..	..	..	..	..	..	..	64	143,400	45	
552-2,													64	143,400	45	
552-3,													66	147,800	49	Still unbroken.
552-2u, 552-5, 552-11,													61 64 65	136,600 143,400 145,000	48 50 51	Bent cold nearly double after being tested.
22,	0·85	0·28	14·01	36	80,900	2	48	107,500	14	55	123,200	27	67	150,000	44	Specimen 22 B still unbroken.
196-1,	1·15	0·84	14·27	..	..	..	..	..	..	..	..	..	69	154,600	46	If the load is calculated on reduced area at the time of fracture, it is equal to 102 tons per square inch. Reduction in area 37 per cent.
196-2,	1 15	0·84	14·27	..	..	..	..	..	..	..	..	..	70	156,800	40	
596,	1·10	0·32	14·48	39	87,400	1	49	109,600	5	..	..	..	63	141,100	37	
597,	1·24	0·16	15·06	49	109,400	2	47	105,300	2	..	..	..	61	136,600	31	
598,	1·54	0·16	18·40	51	114,000	1	39	87,400	1	..	..	..	53	118,800	10	
239,	1·83	0·26	18·55	43	96,300	1	..	..	..	..	..	..	55	123,200	5	
619,	1·60	0·26	19·10	52	116,500	1	41	91,800	1	..	..	..	59	132,000	4	
291,	1·90	0·32	19·98	..	..	..	..	..	..	23	51,500	nil.	..	..	..	
235,	2·10	0·46	21·69	36	80,900	9	34	76,200	12	33	73,900	11	..	..	..	

NOTE 1.—The treatment of the bars is indicated by the letters given under the four headings; D = tested as forged; C, A, and B = reheated to yellow heat, and cooled respectively in air, oil, and water.

NOTE 2.—The appearance of the fractured test bars in the specimens from 3 to 9 per cent. is always coarse and granular, but those with more than 9 per cent. and "water-toughened" are silky and fibrous.

NOTE 3.—The tensile tests are given in tons and lbs. per square inch on original area.

NOTE 4.—The Phosphorus and Sulphur are not given (to save space) as they varied very slightly. The Sulphur averaged 0·06 and the Phosphorus 0·09.

steels with 0 to 4 per cent. Molybdenum and 0·3 per cent. of Carbon, or 0 to 2 per cent. Molybdenum and 0·95 per cent. Carbon, gave results approximating closely to those furnished by Tungsten steel in point of tensile strength, elastic limit, elongation, hardness, and brittleness, when the ratio of added Molybdenum to added Tungsten was as 1 : 2·225.

Molybdenum steels * have been used for tools, rifle barrels, large guns, propeller-shaft forgings, and wire drawing.

Nickel.—The alloys of Nickel and Iron are very important, and are rapidly extending in use. Nickel in the pure state is a metal somewhat less white than Silver, with a melting point of 1,435° C.

Nickel alloys with Iron in all proportions at a temperature between 1,500° and 1,600° C., and a small proportion of Carbon is said to lower its melting point perceptibly; it is harder than Copper or Iron, but will not take temper on sudden cooling.

Commercial Nickel (from 98 to 99 per cent. Nickel) is not difficult to cast but is *cold short*. Cast bars are likely to be spongy, but after hammering are compact and tough.

It has been found that the addition of a very small quantity of pure Magnesium removes from Nickel the occluded gases, and gives a metal capable of being drawn or rolled perfectly free from blowholes. Magnesium in Nickel, like Manganese in ordinary steel, acts as a deoxidising agent, and it improves the ductility and malleability of Nickel to such an extent that the metal may be rolled into thin sheets 3 feet in width.

Aluminium may be used equally well, but if used in excess serves to make the Nickel very much harder. Nickel will alloy with most of the useful metals, and generally increases their hardness, toughness, and ductility.

To show the physical properties of almost pure Nickel in the cast and forged state, we give the following short table from Hadfield's paper on the "Alloys of Iron and Nickel":—†

TABLE LXXVI.

Material.	Condition.	Unannealed.				Annealed.			
		Elastic Limit.	Max. Stress.	Elongation in 2 Ins.	Reduction in Area.	Elastic Limit.	Max. Stress.	Elongation in 2 Ins.	Reduction in Area.
Per cent.		Tons per sq. in.	Tons per sq. in.	Per cent.	Per cent.				
Carbon, 0·08 . . } Iron, 99·80 . . }	Cast	14	20	16	34	Not obtained.			
Carbon, 0·08 . . } Iron, 99·80 . . }	Forged	14	22	47	76	9	18	52	76
Carbon, 0·16 . . } Nickel, 98·80 . . }	Cast	11	16¼	4½	9⅜	Not obtained.			
Carbon, 0·16 . . } Nickel, 98·80 . . }	Forged	14	32¼	45½	57	7	13¼	54	52⅓

It should be noted that whilst the elastic limit of Nickel is slightly less, its tenacity is nearly 50 per cent. greater than that of iron—viz., 32 tons against 22 tons per square inch.

The following results, kindly supplied by Mr. W. H. S. Shakell, give

* *Eng. Mag.*, vol. xxxiii., pp. 91-98. † *Min. Proc. Inst. Civil Engineers*, vol. cxxxviii.

some further particulars of the mechanical properties of nickel in the cast. wrought, and rolled condition :—

TABLE LXXVII.

	Maximum Stress.		Elongation.	Reduction of Area.	Remarks.
	Lbs. per sq. in.	Tons per sq. in.	Per cent.	Per cent.	
Rolled plate 8 ins.,	67,760	30·25	31·4 in 8 ins.	31·5	
Cast bar untreated,	30,985	13·84	6·5 in 2 ins.	6·5	
Casting, ...	85,000	37·95	12 ,,	...	
Wrought nickel, .	96,000	42·86	14 ,,	...	Wrought from 2 × 4 ins. to ½ in. square.
Wrought nickel annealed, . . .	95,000	42·41	23 ,,	...	Wrought from 2 × 4 ins. to ½ in. square.
Rolled nickel, . .	78,000	34·82	10 ,,	...	Very hard, not annealed after rolling from 2 ins. to ⅛ in.

A great deal of information has been published on the properties of Nickel steel, Mr. J. F. Hall, of Sheffield, and Mr. J. Riley having been amongst the early workers in this field. The matter has more recently been most thoroughly investigated by Mr. Hadfield,* and it is to him that we are chiefly indebted for the scientific examination of the properties of steel containing varying percentages of Nickel.

The following table gives the results he obtained on specimens of Nickel steel in the unannealed and in the annealed conditions, with Nickel varying from ·27 to 49·65 per cent., the Carbon being kept low and approximately equal in the whole series :—

TABLE LXXVIII.

Analysis.			Unannealed Test Bars.						Annealed Test Bars.					
C.	Mn.	Ni.	Elastic Limit per Square Inch.		Tensile Stress or Maximum Stress per Square Inch.		Elongation per cent. on 2″.	Reduction of Area per cent.	Elastic Limit per Square Inch.		Tensile Stress or Maximum Stress per Square Inch.		Elongation per cent. on 2″.	Reduction of Area per cent.
			Tons	Lbs.	Tons.	Lbs.			Tons	Lbs.	Tons.	Lbs.		
0·19	0·79	0·27	19	42,560	31	69,440	35	56	20	44,800	28	62,720	37	52
0·14	0·75	0·51	20	44,800	30	67,200	36	62	21	47,040	27	60,540	41	63
0·13	0·72	0·95	25	56,000	33	73,920	31	53	20	44,800	27	60,540	41	63
0·14	0·72	1·92	26	58,240	34	76,160	33	55	22	49,280	31	69,440	36	53
0·19	0·65	3·82	28	62,720	37	82,880	30	54	25	56,000	33	73,920	35	55
0·18	0·65	5·81	28	62,720	41	91,840	27	40	28	62,720	37	82,880	33	51
0·17	0·68	7·65	31	69,440	49	109,760	26	42	30	67,200	45	100,800	26	41
0·16	0·86	9·51	42	94,080	85	190,400	9	18	32	71,680	56	125,440	2	2
0·18	0·93	11·39	65	145,600	94	210,560	12	24	45	100,800	89	199,360	12	26
0·23	0·93	15·48	55	123,200	94	210,560	3	2	...	...	68	152,320	1	1
0·19	0·93	19·64	47	105,280	91	203,840	7	6	45	100,800	87	194,880	5	4
0·16	1·00	24·51	32	71,680	77	172,480	13	14	25	56,000	78	174,720	14	8
0·14	0·86	29·07	25	56,000	38	85,120	33	44	16	35,840	37	82,880	48	51
0·16	1·08	49·65	No test made.						15	33,600	36	80,640	49	53

* *Min. Proc. Inst. Civil Engineers*, vol. cxxxviii.

Below are given the mechanical tests of different Nickel steels made from commercial steel for comparison with the specially prepared bars of Hadfield's Nickel steel—combined Carbon about ·2 per cent., and Nickel about 3·2 per cent.

TABLE LXXIX.

Maximum Stress.		Elastic Limit.		Elongation on 3″.	Contraction on Area.
Lbs. per sq. in.	Tons	Lbs. per sq. in.	Tons.	Per cent.	Per cent.
94,185	42·04	58,995	26·31	26·4	60·83
94,245	42·07	60,770	27·12	25·5	68·58
93,215	41·61	58,740	26·22	25·8	61·33
93,730	41·84	60,770	27·12	25·8	59 81
92,410	41·25	59,550	26·58	28·0	60·74

From these figures it will be noticed that the *elastic limit* of 3 per cent. Nickel steel with ·2 Carbon is about equal to the *tensile strength* of ordinary mild steel, while the *elongation* and *contraction of area* are about the same.

Mr. Francis Sperry, Cleveland, Ohio, gives the following results obtained on testing *transverse* specimens taken from a complete set of Nickel steel gun forgings, made by the Bethlehem Iron Company for the Bureau of Ordnance :—

TABLE LXXX.

	Maximum Stress.	Elongation.	Elastic Limit.
	Lbs. per sq. in.	Per cent. in 2 ins.	Lbs. per sq. in.
Tube, . .	93,200	21·2	58,300
Jacket, . .	99,900	20·4	60,000
Hoops, . .	99,100	20·5	68,200

Tests made on 2 ins.; test pieces ½ in. diameter.

Comparing these results with those usually obtained in similar Naval gun forgings made from ordinary Carbon steel, the tensile strength shows an *increase* of about 10 per cent. with an *increase of elastic limit* from 22 to 28 per cent., while the contraction of area and elongation are but slightly reduced.

The great excellence attained by the Greener Gun is attributed to the use of Nickel steel barrels containing about ·2 per cent. Carbon and 2·75 per cent. Nickel, and the U.S. Bureau of Ordnance is said to have adopted Nickel steel for its small arm barrels.

From Table lxxxi. it will be seen that the Nickel steel shows an average increase of about 31 per cent. in elastic limit, and an average increase of about 20 per cent. in tensile strength, without any great alteration in the ductility as shown by the percentage elongation and contraction of area.

The general effect of Nickel upon iron, and the part played by Carbon in such alloys, have been well summed up by Mr. M. C. White, of the Bethlehem Iron and Steel Co., U.S.A., who has had large experience on a practical scale with various special applications of Nickel steel, and whose remarks are quoted in Mr. Hadfield's paper already referred to.

TABLE LXXXI.—Comparative Tests of Nickel Steel and Best Soft Flange Steel, Specimens Cut from the Plates in Both Cases.

	Tensile Stress or Maximum Stress.		Elastic Limit.		Elongation in 8 ins.	Contraction of Area.
	Lbs. per sq. in.	Tons per sq. in.	Lbs. per sq. in.	Tons per sq. in.	Per cent.	Per cent.
1. Nickel steel containing Per cent. C, 0·08 Ni, 2·69 Mn, 0·36 Per cent. S, 0·038 P, 0·045	64,080	28·60	47,100	21·02	23·25	53·0
	66,370	29·62	44,700	19·95	26 00	53·3
	66,000	29·46	47,400	21·16	25·00	56·3
	67,100	29·95	47,300	21·11	24·50	45·1
	64,800	28·92	...	...	26·00	54·4
	66,200	29·55	48,900	21·38	23·75	49·7
2. Soft steel containing Per cent. C, 0·10 Mn, 0·27 Per cent. S, 0·039 P, 0·040	55,500	24·77	35,700	15·93	26·00	45·6
	54,500	24·33	35,500	15·84	26·00	45·8
	53,900	24·06	32,800	14·62	27·50	52·9
	52,500	23·43	34,060	15·20	32·00	61·8
	53,700	23·97	34,500	15·40	27·00	63·0
	56,500	25·22	36,900	16·47	26·00	63·0

"The *tensile strength* and *elastic limit* of Nickel iron alloys and Nickel steel rise with increasing proportions of Nickel, reaching a maximum at about 20 per cent. Passing this they begin to fall, and elongation increases abnormally up to about 30 per cent. The *ratio of elastic limit to tensile strength* increases with increasing Nickel, at first slowly up to about 10 per cent., when it makes a sharp rise, and then continues gradually up to 20 per cent., after which the ratio falls away rapidly.

"The *hardening effect* of quenching ceases when about 10 per cent. of Nickel is present, but is quite marked in the lower percentages. In this case the effect is heightened by the Manganese, but with ·06 per cent. Manganese it is still decided. Between 10 and 20 per cent. Nickel, neither quenching nor annealing exerts any decided effect. Above 20 per cent., quenching produces a softening effect, which is decided at 30 per cent. Perhaps it would be better to call it a *weakening* effect, as the tensile strength and elastic limit are much lowered, the elongation increased, but the cutting properties shown by turning in a lathe are not perceptibly changed.

"These results refer to alloys of Nickel and iron containing Carbon from ·06 to ·1 per cent., or practically carbonless alloys. The Manganese ranged between ·06 and ·1 per cent.

"Nickel tends to check segregation, due probably to the fact that it raises the melting point of the carbides or cementing material, and causes the whole mass to set more nearly together. This is evidenced by the finer grain of Nickel steel ingots. Nickel does not prevent blowholes, and great care is required in the manufacture to avoid them, as they weld up less easily than in other steels.

"There are many difficulties to be overcome in the handling of Nickel steel as commercially made, where the Carbon ranges from ·15 to ·9 per cent., the Manganese from ·3 to ·9 per cent., and the Nickel from 3 to 30 per cent. It is very susceptible to changes of temperature when containing the usual amounts of Carbon and Manganese, requiring considerable care in heating and working to bring out its best qualities, which are certainly worth all the labour bestowed upon it.

"The fact that Nickel raises the elastic limit of steel is clearly shown by Mr. Hadfield's results, but to give a reason for this effect, which can be

definitely proved, would be difficult. The best explanation is that it strengthens the cementing material up to a certain point (20 per cent. Nickel), and holds in a more rigid matrix the iron crystals which in Nickel steel exist in smaller aggregations. Beyond this the cementing material is not so much strengthened as it is toughened, which accounts for the abnormal increase in elongation."

When Carbon is also present with Nickel in medium and high Carbon steel the presence of the Nickel seems to cause a more intimate combination between Carbon and iron, which toughens the matrix of the iron. Nickel does not seem to interfere, however, with the usual combination of Carbon and iron, but there is probably a double carbide of Nickel and iron formed, as Nickel readily forms carbides.

Steel containing **Nickel** and **Chromium** has been found to give satisfactory results when used for armour plate and also for armour piercing shells, and plates of the following approximate composition have been used :—

	Per cent.	Per cent.	Per cent.
Combined	C, 0·40	Cr, 1·0	Ni, 2·0

here the Nickel may be considered as a *toughening* agent, and the Chromium and Carbon as *hardening* agents.

Nickel-Chrome steel is also largely used on the Continent for manufacture of large guns and also to a more limited extent in this country.

Nickel steel forms an admirable material for forgings for marine and general engineering purposes. From its relatively high tensile strength and elastic limit, without any appreciable reduction in elongation and contraction of area (in comparison with ordinary mild steel), it allows in many instances a considerable margin for reduction in the weight of metal, and consequently a considerable saving in ultimate cost of the forgings.

Some interesting results upon alloys containing Nickel, Chromium, and Silicon made at the Imphy Works have been published by A. Abraham.* Steels of the following composition,

Carbon,	·55 to ·80
Silicon,	·20 to ·50
Manganese,	·30 to ·60
Chromium,	2·00 to 3·00
Nickel,	20·00 to 25·00

tested after forging without any special treatment, gave an elastic limit exceeding 31 tons, with an ultimate tensile resistance of 44½ tons, and an elongation of 45 per cent. on 2 inches. In this condition they were wanting in flexibility, and were better after being subjected to water hardening at a cherry-red heat without further tempering. After this they gave an elastic limit of from 19 to 22 tons, with an elongation of 60 per cent., the elongation taking place over the entire length of the test piece. Another class of steel made at Imphy with Nickel from 12 to 12·5 per cent.; Chromium, ·75 to 1 per cent.; Carbon, ·3 to ·45 per cent., was found to be much harder, breaking almost without stretching in its natural state. After annealing in a wood fire it gave a material suitable for forgings requiring high tenacity and elasticity, the elastic limit exceeding 51 tons, with an ultimate strength of 63½ tons.

Welding.—Nickel under 1 per cent. does not appear to affect the welding properties of steel, but above this percentage welding becomes more difficult, though even with 3 per cent. with care good results can be obtained, as shown by following tests on welded and unwelded specimens containing ·26 per

* *Annales des Mines*, vol. xiv., p. 228, 1898.

cent. Carbon and 3 per cent. Nickel. The tenacity with which the film of Oxide adheres to the surface of the metal does undoubtedly interfere seriously with welding, and this difficulty increased with the percentage of Nickel present. It is not advisable to use Nickel steel with over 1 per cent. for general welding purposes.

Comparative Strength of Welded and Unwelded Nickel Steel.

	Carbon.	Nickel.	Maximum Stress.		Elongation.
			Tons per sq. in.	Lbs. per sq. in.	Per cent.
Welded, . .	0·26	3·00	35·22	78·904	16
Unwelded, .	...	...	35·10	78·622	24

Nickel Steel Wire.—Nickel steel containing as much as 30 per cent. Nickel can be drawn into wire as easily as ordinary steel, and wire of this class contains sufficient Nickel to make the non-corroding qualities of the metal prominent, and is well adapted for hawsers and cable service in salt water. A sample of Nickel steel containing ·4 per cent. Carbon and 27·8 per cent. Nickel, said to be used as torpedo defence netting by the U.S. Navy, gave the following physical test:—

Diameter of Cross Section.	Area of Cross Section. Sq. in.	Reduced Diameter.	Reduced Area. Sq. in.	Contraction of Area. Per cent.	Elongation in 2 in. Per cent.	Load in lbs.	Breaking Strain. Lbs. per sq. in.
0·116	0·01057	0·106	0·0088	16·5	6·25	2,100	198,700

The high tensile strength of this wire, with the comparatively small reduction in elongation and contraction of area, indicates extreme toughness, and at the same time the material is not acted upon, or but very slightly, by salt water.

The *magnetic properties* of Nickel steel alloys show very marked peculiarities. Thus, steel containing 25 per cent. Nickel is scarcely magnetic at all until cooled to a temperature of − 40° C. After exposure to this low temperature, however, it remains magnetisable at ordinary temperatures, and does not recover its original condition until heated to 600° C.

It has been shown by Guillaume that Nickel steel alloys may be divided into two classes as regards their magnetic properties. The first or reversible class comprises those alloys which lose their magnetic properties on heating and recover them on cooling to the same temperature. The second or non-reversible class comprises those alloys which contain 25 per cent. or less of Nickel, and which have magnetic properties similar to those of the 25 per cent. alloy mentioned above.

It has been shown that an alloy with 35·7 per cent. Nickel, and containing Chromium, lost its magnetism at 210° C., whereas a similar alloy without Chromium retained its magnetic properties up to 235° C. Chromium, therefore, seems to have the effect of lowering the temperature of transformation.

The magnetic and electrical properties of iron-nickel alloys have been examined by C. F. Burgess and J. Aston* on a series of alloys in which the impurities have been kept down to the lowest possible point. The magnetic tests were made upon an Eaterline permeameter on the specimens containing from 0·27 to 75·06 per cent. Nickel in an unannealed state, and also after annealing at 675° C. and 1,000° C., and quenching at 900° C.

In the annealed state, up to 1·93 per cent. Nickel the magnetic properties

* *Metallurgical and Chemical Engineering*, vol. viii., No. 1, Jan. 1910, pp. 23-26.

are little inferior to electrolytic iron. Additions of Nickel cause a falling off in quality until at 22·11 per cent. they are very poor, and with 25·20 per cent., 26·4 per cent., and 28·42 per cent. Nickel they are non-magnetic. Further increases of Nickel, 35·09 per cent., 49·08 per cent., and 75·06 per cent., restored the magnetic properties very markedly, the maximum values being obtained with 47·08 per cent. Annealing at 675° resulted in general in an improvement of magnetic quality. Annealing at 1,000° for the bars with smaller Nickel content resulted in an increase of permeability for lower magnetising forces, and bars containing 25·2 and 26·4 per cent. Nickel became appreciably magnetic.

Hysteresis curves were taken on the alloys showing higher permeability, and it was found that the 50 per cent. Nickel alloy had the lowest loss. The electrical resistance was also determined, and it was found that there was a gradual increase of resistance with increase of Nickel up to 22·11 per cent., after which there was a sudden rise at compositions corresponding to those of the non-magnetic alloys. Beyond about 30 per cent. Nickel a decrease is noticed, giving a curve similar to that on the other side of the maximum range. It is suggested that the maximum point might correspond to the compound **Fe_2Ni.**

An alloy containing 35 to 36 per cent. Nickel is known to have a dilatation ten times less than that of Platinum. The expansion in the case of Nickel steels is said to be much more feeble in the magnetic than in the non-magnetic state. Again, it has been shown by Guillaume that a Nickel steel bar containing 15 per cent. Nickel, allowed to cool very slowly from 200° C., contracted until the temperature reached 130° C., when the bar began to expand, and continued to do so until 60° C. If such a bar be heated when below 130° C. very slightly it expands like an ordinary metal, and on again cooling contracts correspondingly until the temperature at which the heating began is reached, when the bar again begins to expand.

As regards non-corrosion, Nickel steel gives far better results than either wrought iron or ordinary mild steel. The following table shows the relative corrosion of wrought iron, soft steel, and Nickel steel (taking wrought iron as a standard), from experiments published in 1900 by Prof. Howe. The specimens treated were exposed for periods of about a year each :—

TABLE LXXXII.

	Sea Water.	Fresh Water.	Weather.	Average.
Wrought iron, ...	100	100	100	100
Soft steel, ...	114	94	103	103
3 per cent. nickel steel, . . .	83	80	67	77
26 ,, ,, . . .	32	32	30	31

Silicon.—See influence of Silicon on steels, p. 369.

Tantalum.—Comparatively little is known of the properties of Tantalum steels, but from researches carried out by Guillet,* it would appear that the effect of Tantalum is too small to enable these steels to attain any special technical importance. Guillet prepared his steels from Tantalum-Iron made in the electric furnace. The steels examined had the following composition :—

* *Comptes Rendus*, vol. cxlv., p. 327.

C.	Ta.	Mn.	Si.	S.	P.
0·12	0·09	0·19	0·12	trace	trace
0·17	0·15	0·15	0·19	..	..
0·18	0·60	0·22	0·24	..	..
0·16	1·05	0·23	0·16	..	..

The steels in the normal condition indicated the usual Pearlite structure with Ferrite, the greater the percentage of Tantalum, the more regular was the distribution of the Pearlite.

The following tables show the influence of Tantalum on the physical properties, in normal and hardened condition —

Normal Steels.

Ta.	Elastic Limit.	Max. Stress.	Elongation.	Reduction of Area.	Brinell Hardness.
	Kgs. per Sq. Mm.	Kgs. per Sq. Mm.	Per cent.		No.
0·09	29·8	41·5	53	67·4	107
0·15	30·4	42·6	31	68·8	107
0·60	31·1	45·3	28	67·2	112
1·05	31·5	47·0	28	62·3	116

It will be noticed from the above that the elastic limit and breaking strength are slightly increased, and the elongation and reduction of area are slightly decreased by the presence of Tantalum.

Hardened Steels.

0·09	46·2	65·0	14·5	71·0	159
0·15	45·7	62·1	15·0	73·1	153
0·60	46·6	65·8	13·0	74·9	155
1·05	49·1	70·0	10·0	55·8	169

The above tests of hardened steels were obtained from specimens hardened at 875° in water at 20° C.

Titanium.—This can be obtained in grey cast iron when smelted from Titanic ores with considerable ease, but it is very difficult to introduce this element into steel. Much of the so-called Titanic steel is quite innocent of the presence of this element. It appears, however, possible to make it from Ferro-Titanium.

As an example of the difficulty of introducing Titanium into steel, the following experiments by Mr. W. H. S. Shakell may be cited. Some of the titaniferous iron sand of New Zealand of the following composition :—

Peroxide of Iron,	67·04
Protoxide of Iron,	30·17
Oxide of Manganese,	0·22
Alumina,	0·16
Silicon,	0·50
Lime,	Trace
Magnesia,	Trace
Titanium,	1·60
Alkalies,	Not determined.
	99·69

was mixed with suitable fluxes and reduced by coke in clay crucibles, and a white pig-iron containing about 2 to 3 per cent. of Titanium was obtained. The metal from three different experiments was then broken and mixed together with a small quantity of oxidised metal and about 8 ozs. of Ferro-Manganese, and re-melted in a crucible furnace, when a steel of the following composition was obtained :—

Iron,	98·400
Combined Carbon,	0·700
Graphite,	Trace
Silicon,	0·112
Manganese,	0·623
Sulphur,	0·098
Phosphorus,	0·030
Titanium,	Nil
	99·963

This ingot forged well under the hammer, and made a fairly good chisel.

This seems very clearly to show that Titanium is much more easily oxidised than Silicon, and this should have an important bearing on the future development of the large Swedish and other iron ore deposits containing Titanium, as if it can be proved that the Titanium in the pig-iron is oxidised completely during the conversion into steel, pig-iron containing Titanium can be used, and it only remains for the blast furnace manager to overcome any difficulties there may be in the smelting of such ores.

Ferro-Titanium is made in the electric furnace, and is sold as " Titanium alloy " ; it may contain 10 to 15 per cent. of Titanium, 5 to 7 per cent. of Carbon, and less than 0·5 per cent. of other impurities. Many contradictory statements have been made as to the effect of Titanium on the properties of steel, and this may be considered as not yet definitely thrashed out. Some investigators * claim that it assists the removal of slag from the metal, renders it free from blowholes, giving increases in the elastic limit and reduction of area. The Titanium itself passes off with the slag unless added in excessive amounts. It has been claimed that Titanium actually reduces the amount of Sulphur and Phosphorus in the metal, but later experiments have not confirmed this, although the obnoxious effect of these elements appeared to be diminished. It is further claimed that Titanium increases the strength of Nickel and Chrome-Nickel steels, acting as a powerful deoxidising agent, and that it also removes Nitrogen from steel, a point on which particular importance has been attached by some metallurgists. Aluminium should not be used in connection with Titanium alloy at any time.

Tungsten.—This is an exceedingly infusible metal which alloys with iron in nearly all proportions to form Ferro-Tungsten. Analyses of rich Ferro-Tungsten now on the market gave the following figures :—

Tungsten,	76·900	Tungsten,	73·05
Iron,	17·950	Iron,	22·55
Silicon,	1·900	Silicon,	0·48
Carbon (combined),	3·300	Carbon (combined),	1·90
Phosphorus,	0·013	Phosphorus,	0·02
		Sulphur,	0·05
		Manganese,	0·34
		Chromium,	1·02
		Copper,	0·01
		Tin,	0·18
		Nickel,	0·22
	100·063		

Ferro-Tungsten can be made in the blast furnace, but such alloys as the above are usually made in the electric furnace. Tungsten can be reduced from the ore (generally Wolframite) by strong ignition with Carbon in crucibles. A good ore has about the following composition :—

* C. V. Slocum, *Mechanical Engineer*, vol. xxiii., pp. 336-337, 1909.

SAMPLE DRIED AT 212° F.

	Per cent.
WO_3,	64·95
Fe_2O_3,	10·98
MnO,	8·05
SiO_2,	10·80
Al_2O_3,	0·97
CaO,	1·80
MgO,	0·25
K_2O, Na_2O,	2·11
	99·91

The reduction of Wolfram ore by coke in the presence of pig-iron in crucibles is comparatively easy if a low percentage Ferro-Tungsten is required, but the resulting Ferro-Tungsten has to be broken up and re-melted to insure a uniform product. Tungsten is chiefly used as an alloy with steel for the production of so-called "self-hardening" steels—*i.e.*, steels which after forging require no quenching or tempering. The following analyses (Table lxxxiii.) show that these steels may vary very considerably in chemical composition, and the temperature at which they can be forged will vary with the composition.

Mr. W. H. S. Shakell informs me he has obtained from a charge of the following composition, a steel which worked remarkably well under the hammer at a low red heat (about 700°), and made capital turning tools :—

Charge.

	lbs.	ozs.
Steel scrap,	26	0
Ferro-Tungsten,	9	0
Silico-Spiegel,	0	10
Ferro-Manganese,	0	2
Swedish pig-iron,	9	4
	45	0

Drillings taken from a resulting ingot gave the following chemical composition :—

Per cent.	Per cent.	Per cent.	Per cent.
Combined **C**, 1·01	**Si**, 0·186	**Mn**, 0·738	**W**, 6·975

A small addition of Tungsten has been found to improve the wearing properties of some classes of chisel steel ; for instance, a steel of the following composition gave good results for the working of pyrites, whilst a steel of similar composition, without the quarter per cent. of Tungsten, failed in a competitive trial :—

Per cent.		Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Fe, 98·40	Combined **C**, 0·63		**Si**, 0·126	**W**, 0·241	**Mn**, 0·522	**S**, ·006	**P**, ·034

A steel containing

Per cent.	Per cent.	Per cent.
Combined **C**, ·57	**Si**, ·21	**W**, ·325

also stood this class of work well, where a somewhat higher Carbon steel (without Tungsten) failed to do the work satisfactorily.

Tungsten when added to low Carbon steel has very little effect on the magnetic properties, but greatly increases the retentiveness in high Carbon steels, and a steel having the following composition :—

Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
Combined **C**, 0·62	**Si**, ·09	**Mn**, ·55	**W**, 5·7	**S**, ·04	**P**, ·045

is found to give very satisfactory results for the manufacture of permanent magnets, used in the construction of electrical meters.

TABLE LXXXIII.

Temperature Worked.	Mushet.	Crescent.	Imperial.
° F.			
1264 Light yellow.	Cracks badly.	Crumbles badly.	...
1155 Yellow.	Forges.	Bends fairly.	Forges, but cracks.
1111 Orange.	Bends well.	...	...
750 Full red.	Bends and hammers close without cracking.	Bends well.	...
700 Low red.	Cracks in bending.	Breaks when bent.	Bends double and hammers close without cracking.
525 Black.	...	Cracks after few blows.	Forges better than at temperatures given above.
	Per cent.	Per cent.	Per cent.
	Mushet—	Crescent—	Imperial—
	C (combined), 1·99	C (combined), 2·06	C (combined), 1·60
	Si, . . 0·09	Si, . . 0·05	Si, . . 0·16
	Mn, . . 0·19	Mn, . . 2·66	Mn, . . 2·11
	W, . . 7·81	W, . . 6·73	W, . . 6·38

N.B.—Crescent appears to forge better at a low yellow heat.
Imperial ,, ,, dull red ,,

These steels are preferably made from charges melted in crucibles, and cast into small ingots about 3 inches square, each weighing about 56 lbs. This steel requires careful heating and "soaking" before hammering, and should not be worked above a full red heat.

Tungsten, in the absence of Carbon, has comparatively little influence on the physical properties of steel, but when alloyed with Carbon steels confers upon them great hardness. The well-known Mushet or self-hardening steel contains about 1·5 to 2·3 per cent. Carbon and from about 5 to 8 per cent. Tungsten. These steels, on heating and allowing to cool in air, are extremely hard, and retain their cutting edges for a long time even when used for machining very hard material; if quenched at a red heat in water in the same way as ordinary steels, they crack.

The following are typical analyses given by Hadfield * :—

Carbon.	Silicon.	Sulphur.	Manganese.	Tungsten.
2·30	1·05	...	2·57	6·12
2·00	1·60	0·02	1·72	8·22
2·05	0·79	0·04	2·30	8·04
1·67	0·33	...	2·53	5·74
2·35	0·15	...	3·38	11·02

The first two are the well-known Mushet steel.

The high percentage alloys, however, are somewhat brittle and can only be used in cases where there is no shock or jar, such as, for instance, cutting purposes in the lathe.

A new class of cutting tool for machine work at very high speeds has lately been introduced, the alloys used being a Chromium-Tungsten or Chromium-Molybdenum steel, specially tempered. The material was exhibited at the Paris Exhibition of 1900 by the Bethlehem Steel Company, and was shown at work on mild steel castings at a speed of 150 feet per minute, without lubricants. The cutting edge of the tool was red hot,

* *Iron and Steel Inst. Journ.*, 1903, vol. ii.

whilst the turnings showed, from the colour when cold, that they had been exposed to very considerable heat. The percentage composition of the tools varies with the work to be done, from about ·75 per cent. of Chromium, with some 4 per cent. of Tungsten and traces of Molybdenum, to 3 per cent. Chromium, 8 per cent. Tungsten, and varying percentage of Molybdenum. For working hard steel or chilled iron the alloy contains about 3 per cent. of Chromium, 5 per cent. of Tungsten, and 4 per cent. of Molybdenum. The great advantage such steel possesses over the ordinary "self-hardening" is imparted to it by the special heat treatment to which it is subjected. The steel is first heated to about 1,000° C., then rapidly cooled down in a bath of molten lead, kept at that temperature for about ten minutes, and then allowed to slowly cool in lime, or some other inert non-conducting body. For some purposes when quite cold it is re-heated to visible red, and allowed to cool in the open air. The surface of the tool is protected during this treatment by being covered with a suitable flux so as to prevent oxidation.

The above method of treating self-hardening steels was only discovered by Messrs. Taylor and White after a most careful series of experiments, as previous to their investigations the greatest care was always taken not to heat these self-hardening steels above 800° C. during forging, any temperature above this spoiling the steel. We owe to them the important discovery that by heating to a temperature *far* above the temperature which the metal would forge, and by *regular cooling*, this great increase of hardness was imparted.

Osmond * in 1892, in experimenting with a Tungsten steel, found that when heated to 830° and quenched at 630°, it remained unhardened, but when heated to 1310° and quenched at a lower temperature—viz., 555°—it was very hard, and he at once noticed the important point that a soft medium or very hard metal could be obtained according as the initial temperature of heating was varied. These results were, however, never published, so that Messrs. Taylor and White's discovery was quite independent of these experiments.

According to Mr. D. Flather,† it appears as if some of the details of the above method are unnecessary. Several brands of steel are at present made at Sheffield, and the method of hardening is said to be much simpler than that above described. The steel is heated to near a welding heat (1,200° C.), and is then either cooled in the air or under an air blast, when, after being ground, it is ready for use.

One such Sheffield brand of steel is that known as the "Speedicut," manufactured by Messrs. Thos. Firth & Sons. The method of manufacture and treatment is kept a secret, so the author is unable to give any information on these points, but it is extremely hard naturally, and will do excellent work at a just visible red heat. It can be forged by any intelligent tool smith, and does not require to be hardened in water or other medium, and allows a lathe to be run at two or three times the usual speed. Probably any method of heating the steel to very high temperature, combined with *slow and regular cooling*, would produce the desired results, these being the two essential conditions in the production of these steels. Such steels as these mark a new epoch in the history of tool steels, and will probably largely revolutionise many of our machine shops.

The influence of Tungsten on mild steel has never been systematically worked out, but some ten to twelve years ago the author conducted a long series of experiments on steel containing about ·1 per cent. of Carbon, made in a Hatton converter. The alloys made varied from traces to 1·58 per

* *Iron and Steel Inst. Journ.*, 1903, vol. ii.
† *Iron and Coal Trades Review*, December 27, 1901.

cent. of Tungsten, and the results of mechanical tests on the samples as rolled and after quenching, together with welding, plating, and cold-bending tests, are given in Table lxxxiv. The results have never been published, as the author hoped to be able to carry out similar series of experiments on higher Carbon steels, and also to confirm the results by further experiments on mild steels on larger bars, but other work has prevented this. So far as these results go, neither the *tensile strength*, *elongation*, nor *reduction of area* appears to be appreciably affected by ·8 per cent. of Tungsten, and even 1·5 per cent. only increases the tensile strength by a few tons. The *hardening effect*, so far as this is indicated by cold-bend tests, is not apparent with ·8 per cent., all the 1 inch round bars bending over close up to this point. With 1·5 per cent. of Tungsten the influence of Tungsten is noticeable in the cold bending, one bar breaking after bending over only 15° and a duplicate at 110°, showing that such metal was distinctly less ductile than that containing less Tungsten, and it is probable that, had there been an alloy between ·8 and 1·5 per cent., this hardening effect might have been noticeable with less Tungsten present. Tungsten apparently has no effect on the welding or forging properties, as shown by the plating out and welding tests, those cases where the material welded badly being evidently due to bad workmanship or some cause other than the presence of Tungsten, as proved by the alloys with larger percentages giving good results. The cold bendings were made with a sledge hammer on the 1-inch bars as rolled.

Since the above was written Mr. Hadfield has read a paper before the 1903 autumn meeting of the Iron and Steel Institute, giving the results of a very complete series of experiments on steels containing from ·1 to 16 per cent. of Tungsten. Up to 1·49 per cent. Tungsten, the Carbon does not exceed ·22 per cent., and the steels may therefore be regarded as strictly comparable with the author's, and the results, with the exception of welding, completely confirm those given in Table lxxxiv. Neither the tensile stress, elastic limit, elongation, nor reduction of area is appreciably affected until the steel contains 3·4 per cent. of Tungsten, and in the annealed samples even 7·47 to 8·3 per cent. does not greatly increase the tenacity. In the bending tests, the samples as rolled showed no apparent hardening until 3·4 per cent. Tungsten was reached, and, when water-quenched from a temperature between 750° and 950° C., not until the steel contained 1·2 per cent. In the author's experiments all the bars *as rolled* bent close, and, in the *quenched* samples, the first hardening effect, which could be credited to the presence of Tungsten, was apparent with the 1·58 per cent. Tungsten steel, there being no alloy between this and the ·8 per cent. The Hadfield compression tests generally confirm the tensile results.

With regard to welding, Hadfield finds that so small a percentage as ·2 of Tungsten prevents welding, whereas the author's samples, with 1·5 per cent., welded well. Appended is a table giving full particulars of Hadfield's results (see Table lxxxv., p. 409). At first sight it seems difficult to explain this different behaviour of the two sets of alloys, but, on carefully examining the analyses of the author's samples, it will be found that the only three containing any appreciable amount of Tungsten which welded badly were K, L, and O, all of which were very low in Manganese, containing less than ·25 per cent. The other samples, fairly high in Manganese, all welded well. On reference to the Hadfield samples, although the percentage of Sulphur is not given in all cases, where it is given it is always high, the lowest percentage being ·1 and the highest ·15; the Manganese in all cases is also very low, the highest percentage being only ·28 and lowest ·18. Bearing these facts in mind, it does not seem improbable that any tendency to red shortness, induced by the presence of Tungsten, may have been greatly increased by

TABLE LXXXIV.—AUTHOR'S RESULTS.

Analyses and Mechanical Tests of Tungsten Steel.

No.	Analyses.						Mechanical Tests.													Remarks.
							Cold Tests		Hot Tests.		Machine Tests on Bars as Rolled in Tons per Square Inch. Elongation, 8 inches.					Machine Tests on Quenched Bars in Tons per Square Inch. Elongation, 8 inches.				
	Silicon.	Phosphorus.	Manganese	Sulphur.	Carbon.	Tungsten.	Bars as Rolled.	Rolled Bars Quenched.	Plating.	Welding.	Maximum Stress.	Elastic Limit.	Elongation.	Reduction of Area.	Fracture.	Maximum Stress.	Elastic Limit.	Elongation.	Reduction of Area.	Fracture.	
A	trace	·071	·394	·064	·100	nil	Bent over close.	Bent over close.	Very good.	Very good.	27·3	20·9	27·8	59·0	Silky.	37·5	25·9	15·6	50·9	Silky.	
B	,,	·075	·341	·040	·095	trace	,,	,,	,,	,,	27·7	21·7	23·1	43·2	..	39·0	25·9	17·5	50·0	,,	
C	,,	·076	·537	·054	·120	,,	,,	,,	,,	,,	29·8	21·2	25·6	56·2	..	42·9	26·3	15·0	49·1	,,	
D	,,	·040	·207	·029	·070	,,	,,	,,	Fair.	Good.	24·3	17·4	28·1	76·0	..	5·9	16·1	23·7	65·5	,,	
E	,,	·070	·570	·054	·130	,,	,,	,,	Very good.	Very good.	30·3	21·0	15·8	42·3	Crystalline.	40·9	25·1	17·5	52·3	,,	
F	,,	·074	·561	·052	·135	0·010	,,	Broke at angle 15°.	,,	,,	30·5	21·2	23·7	44·8	..	39·7	28·9	10·6	45·0	,,	
G	,,	·070	·382	·071	·110	0·050	,,	Parallel, then broke.	Poor.	Poor.	28·2	21·1	25·0	58·3	..	39·2	26·3	13·7	32·7	Crystalline.	Broke near mark.
H	,,	·049	·241	·046	·070	0·210	,,	Bent over close.	Fair.	Very good.	24·8	17·2	26·9	63·7	..	35·1	21·4	15·2	55·3	Silky.	
I	,,	·070	·491	·024	·110	0·285	,,		Very good.	,,	29·6	22·3	21·2	47·7	..	39·4	25·6	11·2	14·2	Crystalline.	
J	,,	·068	·474	·017	·115	0·310	,,	,,	,,	Fair.	29·0	21·9	25·0	59·5	..	39·4	26·3	13·1	30·6	Silky.	
K	,,	·063	·231	·043	·115	0·361	,,	Broke at angle 140°. Check ,, 15°.	,,	Bad.	26·8	20·3	25·0	55·8	..	41·1	28·8	11·8	32·0	Crystalline.	
L	,,	·048	·184	·031	·070	0·415	,,	Bent over close.	Poor.	,,	22·6	17·8	27·5	78·8	..	29·8	18·1	25·0	65·2	Silky.	
M	,,	·053	·416	·043	·130	0·517	,,	Bent over close, then broke. Check ,,	Very good.	Very good.	27·9	20·3	23·4	62·1	..	44·2	28·5	15·6	46·8	,,	
N	,,	·050	·369	·035	·125	0·524	,,	Bent over close.	,,	,,	28·7	20·0	20·6	41·9	..	43·1	27·1	15·6	46·4	,,	,,
O	,,	·073	·243	·054	·080	0·731	,,	,,	,,	Bad.	27·6	21·3	21·9	38·6	..	40·3	24·7	14·3	43·8	,,	
P	,,	·076	·372	·053	·145	0·800	,,	,,	,,	Very good.	28·9	21·5	25·0	58·5	..	43·6	26·8	11·8	52·7	,,	
Q	,,	·035	·468	·019	·220	1·580	,,	Broke at angle 15°. Check ,, 110°.	,,	,,	31·1	19·2	24·7	64·2	..	40·8	22·9	9·3	3·6	,,	,,

TABLE LXXXV.—HADFIELD'S RESULTS.

GENERAL TABLE, SHOWING ANALYSIS, ELASTIC LIMIT, BREAKING LOAD, ELONGATION, REDUCTION OF AREA, BENDING AND WELDING QUALITIES OF UNANNEALED AND ANNEALED FORGED TUNGSTEN-IRON ALLOYS.

Marks.	Analyses per cent.							Limit of Elasticity per Square Inch.	Maximum Stress per Square Inch on Original Area.	Total Elongation per cent. on 2 Inches.	Reduction of Area per cent.	Appearance of Fractured Test Bar.	Bending Tests of Unannealed and Annealed Forged Bars, Inch wide and Inch thick.	Welding Test.
	Carbon.	Silicon.	Sulphur.	Phosphorus.	Manganese.	Tungsten.		Tons.	Tons.					
A	·13	·03	·12	·06	·22	0·10	Unannealed.	20·0	25·50	35·30	60·74	Dark granular; fibrous and silky.	Double, unbroken.	...
							Annealed.	14·5	22·50	43·10	65·46		,, ,,	...
B	·15	·04	...	...	·22	0·20	Unannealed.	22·5	27·50	40·85	60·74	Granular; fibrous; silky at edges.	,, ,,	Would not weld.
							Annealed.	16·5	22·50	46·30	66·48		,, ,,	
C	·15	·07	·10	·08	·29	0·40	Unannealed.	24·0	31·00	33·00	59·80	Granular; fibrous; silky.	,, ,,	...
							Annealed.	18·0	25·50	39·60	60·10	,, ,, ,,	,, ,,	...
D	·13	·04	...	...	·18	0·35	Unannealed.	20·0	27·50	37·35	58·34	Granular; fibrous; silky at edges.	,, ,,	Would not weld.
							Annealed.	16·5	23·00	44·95	68·90		,, ,,	
E	·21	·05	...	...	·18	0·81	Unannealed.	29·0	32·25	35·28	63·36	Dark granular; fibrous; silky.	,, ,,	,,
							Annealed.	18·0	26·25	37·60	53·26		,, ,,	
F	·22	·05	...	...	·18	1·20	Unannealed.	25·0	32·50	25·75	49·34	Dark granular; fibrous and silky.	,, ,,	,,
							Annealed.	17·5	27·00	37·68	54·38		,, ,,	
G	·21	·07	·12	·07	·25	1·49	Unannealed.	20·0	34·50	26·35	46·72	Granular; fibrous; silky at edges.	,, ,,	,,
							Annealed.	19·5	28·50	36·90	54·88		,, ,,	
H	·28	·06	·10	·06	·28	3·40	Unannealed.	31·0	41·00	29·50	51·80	Granular; fibrous; silky at edges.	110°, broken.	...
							Annealed.	23·0	34·00	33·90	53·02		Double, unbroken.	...
I	·38	·11	...	...	·20	7·47	Unannealed.	37·5	63·00	14·15	18·42	Very fine dark crystalline, with dark spot at edge from which fracture radiates.	84°, broken.	...
							Annealed.	24·0	40·00	25·65	38·46		Double, unbroken.	...
J	·46	·08	...	·06	·28	8·33	Unannealed.	45·0	64·00	2·50	2·48	Fine crystalline, with small defect at edge.	45°, broken.	...
							Annealed.	25·5	42·50	22·80	32·62		Double, unbroken.	...
K	·63	·10	...	...	·25	10·56	Unannealed.	55·0	80·00	5·19	4·80	Very fine dark crystalline.	10°, broken.	...
							Annealed.	28·5	48·00	10·00	10·24		Double, unbroken.	...
L	·76	·19	...	...	·28	15 65	Unannealed.	* ...	...	...	...	... ...	5°, broken.	...
							Annealed.	27·5	57·00	3·45	2·56	... ...	168°, ,,	...
M	·78	·15	·15	·04	·27	16·18	Unannealed.	Bar had been measured up to 50 tons, but no set observed.	Broke short at 55 tons.	0·46	0·28	Fine crystalline.	3°, ,,	...
							Annealed.	27·5	43·00	1·45	0·74	,,	95°, ,,	...

* Too hard to machine in unannealed condition.

the absence of Manganese and the presence of a comparatively large percentage of Sulphur, and, given a larger percentage of Manganese and lower Sulphur, some of the Hadfield samples which refused to weld might have given much better results. It thus seems probable that Tungsten *per se* up to 1·5 per cent. does not prevent welding of mild steel, except in cases where the general composition of the steel would lead us to expect doubtful results, when it increases the evil. The action, however, of Tungsten on the welding properties requires further experimental evidence before the matter can be considered finally settled.

Tungsten steels are largely used for permanent magnets, and G. Hannack * has pointed out that Carbon and Tungsten are by far the most important constituents of magnet steels. Manganese is found to reduce the capacity, and should not be higher than 0·2 per cent.; Silicon in small quantities is not detrimental, and Sulphur and Phosphorus have no influence of the capacity or permanence of magnet steels. Copper and Nickel are found to be detrimental. A steel of the following composition is stated to be excellent for magnets:—**C** 0·6, **W** 5·37, **Mn** 0·18, **P** 0·02, **S** 0·038, **Si** 0·25, **Cu** 0·004.

For the best results, this steel should be hardened at about 850° C.

Molybdenum may be used instead of Tungsten, but Chromium is inferior in its effect.

Uranium.—Very little is known of the properties of Uranium steels, but Uranium † is said to increase the hardness, toughness, and elasticity of steel, although not to the same extent as Vanadium, Chromium, Nickel, or Tungsten. Uranium steels are claimed to be specially suitable for ordnance and armour plate.

Vanadium.—The general effect of Vanadium on steel seems to be to increase the tensile strength and elastic limit and somewhat reduce the elongation.

The experiments made during the last few years—*i.e.*, since Vanadium became obtainable at a more reasonable price—have demonstrated that it is probably one of the most powerful metals for alloying with steel yet discovered. One or two-tenths per cent. of Vanadium raises the elastic limit and tensile strength of mild or low Carbon steel by about 50 per cent., and in some cases even more.

Vanadium apparently acts to some extent in the same way as Aluminium as a deoxidiser, and it is also claimed that it removes Nitrogen in form of Nitrides, thus reducing the occluded gases in the steel. It appears to act directly in several different ways, in low and medium Carbon steels it toughens the metal mainly by its solid solution in the Carbonless portion or Ferrite; it also forms complex Carbides, which, especially with Chromium or Nickel, greatly strengthen the steel, and it seems to have a physical influence also, promoting the even distribution of the Carbon and considerably retarding constitutional segregation; from experimental evidence there is the strongest reason to believe that a very small percentage of Vanadium will largely enable the steel to resist that deterioration which, under continued vibration, leads to brittleness, and is one of the most serious dangers which engineers have to face in these days of high-speed engines with large moving parts.

Samples of steel alloyed with very small quantities of Vanadium have been produced and have given extraordinary results when tested mechanically. The following are the results obtained with some experimental bars and plates from crucible steel with and without Nickel, for which I am indebted to the late Mr. A. F. Wiener. The experiments were conducted by Prof. Arnold:—

* *Stahl und Eisen*, 1908, vol. xxviii., pp. 1237-1240; see also *Mechanical Engineer*, 1910, vol. xxv., pp. 331-332.

† *Oesterr. Zeit. für Berg. und Huttenwesen*, vol. lvii., p. 313.

TABLE LXXXVI.—Influence of Vanadium on Ordinary Mild Steel and on Mild Nickel Steel.

No.	Carbon.	Vanadium.	Nickel.	Silicon.	Manganese.	Sulphur.	Phosphorus.	Area.	Elastic Limit per Square Inch.		Maximum Stress per Square Inch.		Elongation per cent. in 2 Inches.	Reduction of Area.
								Sq. Ins.	Lbs.	Tons.	Lbs.	Tons.		Per cent.
Bars as rolled.														
682*	0·22	None.	None.	0·083	0·24	0·02	0·015	0·25	57,615	25·72	68,650	30·64	33·5	60·1
683	0·20	0·27	,,	0·092	0·48	...	...	,,	83,776	37·40	105,500	47·08	22·0	51·4
684	0·25	None.	3·35	0·084	0·46	...	...	,,	73,024	32·60	94,528	42·20	26·5	52·8
685	0·24	0·28	3·38	0·091	0·48	...	...	,,	112,650	50·28	152,678	68·16	17·0	36·3
Bars reheated to 800°, allowed to cool in air.														
682*	0·22	None.	None.	0·083	0·24	0·02	0·015	0·25	51,856	23·16	63,428	28·32	37·5	64·5
683	0·20	0·27	,,	0·092	0·48	...	...	,,	63,168	28·20	81,190	36·24	29·5	59·4
684	0·25	None.	3·35	0·084	0·46	...	...	,,	70,890	31·64	92,054	41·08	28·5	56 9
685	0 24	0·28	3·38	0·091	0·48	...	...	,,	103,760	46·32	121,856	54·40	22·0	51·2
682†	0·22	None.	None.	0·083	0·24	0·02	0·015	0·355	43,130	19·26	63,930	28·53	2 ins. 42·0 4 ,, 31·0	51·5
683	0·20	0·27	,,	0·092	0·48	...	...	0·363	75,600	33·74	99,140	44·27	2 ,, 19·0 4 ,, 17 0	41·6
684	0 25	None.	3·35	0·084	0·46	...	...	,,	59,850	26·72	90,050	40·22	2 ,, 18·0 4 ,, 21·2	40·5
685	0·24	0·28	3·38	0·091	0·48	...	...	,,	91,840	41·01	158,873	70·93	2 ,, 10·0 4 ,, 9·7	11·9
695	0·18	0·61	None.	0·148	0·43	...	...	0·375	93,856	41·87	122,124	54·52	2 ,, 20·0 4 ,, 15·0	34·4

* Nos. 682 to 685 $\frac{3}{4}$-inch round bars. † Nos. 682 to 685 and 695 rolled into 3-inch by $\frac{3}{8}$-inch plate. Test bars 1 inch wide.

Mark.	Size.	Bending Tests.		Remarks.
		Bent Cold over a Radius of	Bending Angle.	
682	12 inches × 1 inch × $\frac{3}{8}$ inch.	$\frac{3}{8}$ inch.	180°, unbroken.	Closed without fracture.
683	,, ,, ,,	,,	,, ,,	Broke on closing. Steel much stiffer than 682.
684	,, ,, ,,	,,	,, ,,	Cracked on closing.
685	,, ,, ,,	,,	120°, broke.	Steel very stiff.
695	,, ,, ,,	,,	180°, unbroken; very stiff.	Broke on closing.

The round bar, 682 of ordinary steel, has an exceptionally high elastic limit, but in the plate samples is nearer normal, and no explanation of this can be given. It will be noticed that ·27 of Vanadium has raised the elastic limit 12 tons, and the maximum stress 16 tons per square inch, with only a fall of 11 per cent. in the elongation and 9 per cent. in the reduction of area, thus having a greater influence than 3·35 per cent. of Nickel. In the Vanadium-Nickel steel, 685, ·28 per cent. of Vanadium has raised the elastic limit 18 tons, and the maximum stress 26 tons per square inch, giving a steel with an elastic limit of 50 tons, and a maximum stress of over 68 tons per square inch, with an elongation of nearly 17 per cent., and a reduction of area of over 36 per cent.

The above results are confirmed by some given in the *Engineering and Mining Journal* of New York, of 18th August, 1900, where a wrought-iron bar containing 0·5 Vanadium gave 39 tons maximum stress with 12 per cent. elongation, compared with 24·5 tons and 19 per cent. elongation for the unalloyed iron. On annealing, the Vanadium bar gave 33·7 tons maximum stress with 32 per cent. elongation. A mild steel of 30 tons maximum stress and 17 per cent. elongation when alloyed with 1 per cent. Vanadium, gave a maximum stress of 61 tons and 14 per cent. elongation as rolled, and after annealing, 45 tons and 20 per cent. elongation.

When using Vanadium to alloy with steel it must be borne in mind that the element acts in the same direction as, but to a much more marked extent than, Carbon in steel, and that the percentage of Carbon must therefore be controlled with special care.

The following are some results with high Carbon steels kindly supplied me by Mr. Wiener, a bar of pure iron with ·85 per cent. of Vanadium being included in the tests for comparison :—

TABLE LXXXVII.—Influence of Vanadium on high Carbon Steels.

Ingot Number.	Analyses.			Mechanical Results.			
	Combined Carbon.	Vanadium.	Aluminium.	Elastic Limit per Sq. Inch.	Maximum Stress per Sq. Inch.	Elongation per cent. in 2 Inches.	Reduction of Area.
	Per cent.	Per cent.	Per cent.	Tons.	Tons.		Per cent.
617 Steel,	1·06	0·14	0·07	43·0	67·9	6·5	6·9
618 ,,	1·02	0·29	0·09	43·2	76·2	8·5	10·0
619 ,,	1·00	0·58	0·36	64·8	85·5	7·0	7·6
620 Iron,	0·05	0·85	0·05	20·4	26·1	37·0	72·0
621 Steel,	0·80	1·11	0·45	54·0	77·1	10·0	17·6
622 ,,	1·04	0·77	0·21	58·8	84·0	7·5	9·3

Test bars. ¾-inch rounds.

The results of the mechanical tests prove beyond doubt the remarkably powerful influence of Vanadium on iron and steel. A pure iron ingot without Vanadium yields a bar having an elastic limit of 12 tons, and an ultimate stress of 21 tons per square inch, and also a reduction of area of about 75 per cent. Therefore, ·85 per cent. of Vanadium has raised the elastic limit 8 tons, and the ultimate stress 5 tons per square inch without appreciably reducing the ductility; its influence, however, on iron is not nearly so marked or extraordinary as its action upon steel.

A nearly pure iron and Carbon steel containing about 1·1 per cent. of Carbon has an elastic limit of about 30 tons, an ultimate stress of about 60 tons per square inch, together with an elongation on 2 inches and a reduction of area of about 8 per cent. each. On reference to the table, it will be seen that without appreciably altering the ductility, ·14 per cent. of Vanadium has raised the elastic limit 13 tons and the maximum stress about 7 tons per square inch.

Without lowering the ductility (if anything, raising it) ·3 per cent. of Vanadium raises the maximum stress to 76 tons, and ·6 per cent. raises it to 85 tons per square inch. There seems to be no advantage in adding beyond ·6 per cent., as the steel containing ·77 per cent. gave practically the same results as that containing ·58 per cent. of Vanadium.

The elastic limit of nearly 65 tons per square inch possessed by the steel last named is more than remarkable.

Vanadium has such a very high melting point that it is very difficult, if not impracticable, to alloy it with steel in the ordinary plant available at steel works. Ferro-Vanadium, however, which should contain not less than 25 or over 35 per cent. Vanadium, will alloy easily with steel either in the crucible or the open hearth furnace. Losses by oxidisation are possible, but can be largely avoided, and with care and the exercise of proper technical skill by the steel-makers this loss should never exceed ·10 per cent., and normally not more than ·07 per cent.; thus in open hearth practice to obtain ·3 per cent. of Vanadium in the steel it should only be necessary to add a quantity of the alloy equivalent to ·37 per cent. Vanadium.

The Ferro-Vanadium used should be as pure as possible. The alloy commercially obtainable sometimes contains appreciable quantities of Carbon or Aluminium, either of which elements, if added haphazard to steel, may render the effect of the Vanadium on steel partly illusory or disappointing. An alloy which has a low melting point, and which gives very good results in actual practice, contains about 30 to 40 per cent. Vanadium, 6 to 7 per cent. Silicon, and about 3 per cent. of Aluminium.

During the last few years several systematic researches on Vanadium steels have been carried out and the results published,* and I am indebted to Mr. Kent Smith for the following information as to the influence of Vanadium, based on his own experimental work. It will appear from his results that, quite apart from the question of cost, the useful application of Vanadium is confined to alloying very small percentages, and in the direction of the quaternary rather than in that of the ternary steels.

The following table illustrates the effect of Vanadium, both alone and when alloyed with Chromium, in raising the ultimate stress and the yield point without very appreciably reducing either the elongation or reduction of area :—

* Sankey and Kent Smith, *Inst. Mech. Eng.*, December, 1904; Guillet, *Iron and Steel Inst. Journ.*, vol. ii., 1905; Kent Smith, *ibid.*; Kent Smith, *Soc. Chem. Industry*, March, 1906; Kent Smith, *Staffordshire Iron and Steel Inst.*, February, 1906.

TABLE LXXXVIII.

Reference Letter.		Yield Point. Tons per Sq. In.	Ultimate Stress. Tons per Sq. In.	Elastic Ratio.	Elongation. Per cent. on 2".	Reduction of Area. Per cent.
	CRUCIBLE STEELS (Carbon, ·22% to ·25%)—					
A	Plain Carbon, Manganese, ...	16·0	27·0	·592	35·0	60·0
B	,, +0·5% Chromium, ...	22·9	34·0	·673	33·0	60·6
C	,, +1·0% ,, ...	25·0	38·2	·654	30·0	57·3
D	,, +0·1% Vanadium, ...	28·5	34·8	·819	31·0	60·0
E	,, +0·15% ,, ...	30·4	36·5	·833	26·0	59·0
F	,, +0·25% ,, ...	34·1	39·3	·867	24·0	59·0
G	,, +1·0% Chromium+0·15% Vanadium,	36·2	48·6	·745	24·0	56·6
H	,, +1·0% ,, +0·25% ,,	49·4	60·4	·818	18·5	46·3
I	NICKEL STEEL, ...	26·0	42·0	·619	24·0	50·0
K	,, +0·2% Vanadium, ...	52·1	57·9	·899	20·5	52·4
	OPEN HEARTH STEELS (Carbon, ·25% to ·27%)—					
L	Plain Carbon, Manganese, ...	17·7	32·2	·549	34·0	52·6
M	,, +1·0% Chromium+0·15% Vanadium,	34·4	52·6	·654	25·0	55·5

The very marked influence of oil tempering on the static qualities of the Chrome Vanadium and Nickel Vanadium steels is shown in the following table, due in all probability to the retarding action which Vanadium apparently has on the segregation of the Carbides :—

TABLE LXXXIX.

Reference No.		Yield Point. Tons per Sq. Inch.	Ultimate Stress. Tons per Sq. Inch.	Elastic Ratio.	Elongation on 2 Inches. Per cent.	Reduction of Area. Per cent.
	OPEN HEARTH CHROME VANADIUM STEELS—					
N	Tempered rolled bar of steel, M, Table lxxxviii., .	43·4	53·6	·809	22·0	56·6
	Similar Steels—					
O	Motor crank-shaft forging, .	48·5	57·1	·849	22·5	49·0
P	Hollow gun axle, ...	45·6	53·2	·857	20·0	54·9
Q	Automobile (solid) driving axle, ...	43·5	53·7	·810	21·0	60·7
	NICKEL VANADIUM STEEL—					
R	Tempered rolled bar of steel, K, Table lxxxviii., .	80·3	82·7	·971	14·5	50·5
	OPEN HEARTH STEEL—					
S	Mild Chrome Vanadium steel, as rolled, ...	21·8	27·6	·789	38·0	63·0
S_1	The same, quenched from 850° C., ...	34·1	45·7	·746	22·0	61·6

The steel marked **S** is suitable for case hardening.

It is not only under static stress that Vanadium quaternary steels give such remarkable results, but under dynamic and vibratory stress the results are exceptionally good. By the judicious use of Vanadium, a material combining high tensile strength with resistance to sudden shock and vibratory stresses, so urgently required by engineers to meet the requirements of modern engineering practice, can be produced.

In the following tables (xc., xci., xcii.) some results are given, an exceptionally high-class steel, far superior to most Carbon steels, being tested for comparison; this steel, marked **T**, gave the following results in the testing machine:—

Reference No.	Elastic Limit. Tons per Sq. Inch.	Ultimate Stress. Tons per Sq. Inch.	Elongation on 2 Ins. Per cent.	Reduction of Area. Per cent.
T	18·5	30·2	40·5	60·7

TABLE XC.—Alternating Stress (Arnold's Method).

Reference No.	Table.	Number of Alternations before Fracture.
T Carbon steel, ...	...	1,000
O Vanadium Chrome steel, . . .	lxxxix.,	1,500
P ,, ,, . . .	,,	1,600
Q ,, ,, . . .	,,	1,700

The following results further illustrate the influence of Vanadium and Chromium on the static and dynamic qualities of steel:—

TABLE XCI.

Reference No.	Elastic Limit. Tons per Sq. Inch.	Ultimate Stress. Tons per Sq. Inch.	Elongation on 2 Inches. Per cent.	Reduction of Area. Per cent.	Resistance to Alternating Stress (Arnold) before Fracture.	Resistance to Rotary Vibration (Stead). Reversals before Fracture.
T Carbon steel, . .	18·5	30·2	40·5	60·7	1,050	6,600
U Vanadium Chr. steel,	21·0	39·0	34·5	53·1	2,200	...
V ,, ,,	29·4	42·9	33·0	60·7	2,100	65,700

In **U** and **V** we have two steels combining high tensile strength with ductility, and at the same time showing remarkable resistance to vibration and sudden shock.

TABLE XCII.—Impact Tests (Izod's Method).

Reference No.	Table Reference for Tensile Results.	Resistance to Sudden Shock. Foot-lbs.
T Carbon steel, ...		13
O Vanadium Chrome steel, . .	lxxxix.	11
P ,, ,, . .	,,	10
Q ,, ,, . .	,,	12
U ,, ,, . .	xci.	16
V ,, ,, . .	,,	15

The above steels are all comparatively low in Carbon, but that very high tensile strength, combined with ductility, can be obtained by alloying Vanadium with higher Carbon steels is shown by the results given below, obtained with a ·45 per cent. Carbon steel:—

	Elastic Limit. Tons per Square Inch.	Ultimate Stress. Tons per Square Inch.	Elastic Ratio.	Elongation on 2 Inches. Per cent.	Reduction of Area. Per cent.
As forged, .	44·95	77·92	·577	19·0	50·4
Tempered, .	91·69	101·72	·901	7·5	17·7

In the case of ordinary Carbon steels, when the tensile strength is considerably increased by additions of Carbon, the ductility and resistance to shock are rapidly reduced, but, by the addition of Vanadium instead, the static strength is greatly increased, while the ductility and resistance to sudden shock are not appreciably decreased.

Judging from the results obtained in practice, Vanadium used in combination with Chromium seems to give the best results. A steel containing from ·24 to ·28 per cent. of Carbon, 1·0 per cent. Chromium, and ·16 per cent. Vanadium is recommended by Kent Smith for rapidly moving parts subjected to alternating and other complex stress, and this class of steel is more largely used than the higher Carbon steel. It can be used both in the annealed and oil-tempered condition, and in the former state has a tensile strength of about 36 tons with an elastic limit of 27 tons, and an elongation 30 per cent. on 2 inches; oil-tempered it gives 59 tons tensile, 50 tons elastic limit, and 18 per cent. elongation with 57 per cent. reduction of area. For springs a somewhat higher Carbon, ·41 to ·47 per cent., with ·80 to ·90 per cent. of Manganese, is recommended, and it is claimed that springs made from this steel withstand repeated alternations of stress in the neighbourhood of the elastic limit to a far greater extent than Carbon steels without taking permanent set. This steel has also given very satisfactory results for gears for motor cars, and a somewhat higher Carbon and lower Manganese steel has been used in the United States for tires.

So far as my own experience goes, I have seen some excellent results with Chrome Vanadium steels in cases where a high tensile strength combined with resistance to vibration and shock were required, and, although at present the use of this steel is limited, it is probable that, if the cost of Vanadium is reduced, it will be much more largely used.

The present price of the metal Vanadium is high, and, consequently, its use in steel manufacture is limited to high-class steels required for special purposes; but the small quantities in which it is used should enable Vanadium steel to compete, as regards price, with Nickel steels containing from 3 to 4 per cent. of Nickel.

High-speed Tool Steel.—During the last fifteen years great improvements have been made in the manufacture and heat treatment of tool steels, as the result of which cutting speeds are now used which appeared to be impossible a few years ago. These improvements depend mainly on the properties induced by the addition of special ferro-alloys, such as Tungsten, Chromium, Molybdenum, and Vanadium.

The following table, taken from an article by Dr. Carpenter, gives the compositions of four types of tool steels, with comparative figures of their speed of cutting medium hard steel:—

Make of Steel.	C.	Si.	Mn.	W.	Cr.	V.	Speed per Minute in Feet.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.	
Jessop Carbon, . .	1·047	0·206	0·19	..	0·207	..	16
Mushet self-hardening, .	2·15	1·044	1·58	5·44	0·40	..	26
Taylor-White, . .	1·85	0·150	0·30	8·00	3·80	..	60
Modern high-speed steel,	0·67	0·043	0·11	18·91	5·47	0·29	100

The increase in cutting speed above noted is due to variation in composition and almost equally due to improvements in heat treatment.

The Carbon steels as mainly used for tool purposes up to the year 1894 contained only small quantities of constituents other than iron and Carbon; the Mushet self-hardening or air-hardening steels, which began to come into general use about 1894, contained considerable amounts of Tungsten besides high Carbon, Silicon, and Manganese. The original Taylor-White tool steel, which may be considered to have introduced rapid cutting tools, contained larger quantities of Tungsten and Chromium with high Carbon and low Silicon and Manganese. The modern high-speed tool steel consists essentially of an Iron-Tungsten-Chromium alloy with medium Carbon (0·6), and in some cases a small amount of Vanadium; Molybdenum is sometimes used to replace some of the Tungsten. The most suitable heat treatment of these steels differs greatly from that of Carbon steels, for whereas in hardening the Carbon and Mushet tools the greatest care had to be taken not to overheat them, the Taylor-White and modern rapid tool steels cannot be overheated, in order to get the full cutting value out of them, they have to be almost melted. For the manufacture of high-speed tool steel, the materials which must be of the highest quality are melted in crucibles. Each crucible takes a charge of 80 to 50 lbs., according to the number of times it has previously been used; after melting, the charge is either teemed into a ladle, which receives the contents of several crucibles and then into an ingot mould, or direct into the mould. After solidification, the ingot is stripped and cropped as usual.

The steel is so hard in the cast condition that it has to be softened previously to being worked by a prolonged heating at a temperature of about 800° C. in a gas-heated furnace. This last treatment being continued sometimes for two days. At the end of this treatment the ingot is ready for forging. For this purpose it is heated to about 1,000° C. in a clear coke fire, and then forged to the required size, and sometimes rolled as a finishing operation. The material then undergoes a second annealing at about 800° C. for from 12 to 18 hours, according to its section, and is then again heated to 1,000° C., and forged to any desired shape. When cold it is ground on a dry stone or dry emery wheel. It is now ready for the high-heat treatment, for which it is heated in a smith's fire until the nose begins to melt, and is then completely cooled in an air blast, or in some cases, after the temperature has fallen to 900° C., it is oil-quenched. In some cases the tool also receives a low-heat treatment at a temperature of 625° C.

CHAPTER XVIII.

HEAT TREATMENT OF STEEL.

What is called the "heat treatment" of steel—*i.e.*, the whole of the thermal conditions to which the material is subjected from the time it is cast until it is ready to leave the manufacturer's hands—is now recognised as being of the utmost importance in steel manufacture, and is receiving more and more attention from practical men. The great influence which heating to varying temperatures has upon the crystalline structure and physical properties of the metal can be demonstrated by a very simple experiment which anyone can perform for himself. Take a piece of steel, 10 to 12 inches long, and about $\frac{3}{4}$ to 1 inch in diameter, nick it at distances of about 1 inch apart, and then heat one end to a full welding heat in a smith's forge and allow to cool naturally or quench in water. Now break off pieces of the bar at the points where it has been nicked and compare the fractures of the different pieces. The first piece which has been heated to a full welding heat will have a coarse crystalline structure, and will readily break off at the first blow of the hammer, the next inch will be finer in fracture, and each succeeding piece will be finer than the last until that part of the steel is reached which has only been slightly heated, when the differences in fracture will be hardly perceptible, the grain being uniformly fine.

The crystalline structure of steel in relation to heat is affected principally by five factors—viz., temperature, time of heating, mass, rapidity of cooling, and whether the steel is allowed to cool slowly undisturbed, or whether it is forged or rolled during the cooling period. The question of mass is most important, and so far as systematic experimental work is concerned little has been done to investigate its influence, although no doubt many manufacturers have studied this question so far as it relates to their own particular branch. It is of course intimately connected with time, as the larger the mass the longer the time necessary to heat it to its centre, and thus the outside of a large casting or forging may be heated for a considerably longer period than the inside, and consequently different parts of the same forging will have been subjected to different heat treatment. The marked influence of work on the structure, and consequently on the physical properties of steel, is shown in the case of welding. On heating a piece of steel to full welding heat and allowing it to cool undisturbed, it will have a large crystalline structure and be comparatively brittle, whereas the same steel, if well hammered to weld it to another piece, will be fine in structure, tough and ductile.

In everyday practice steel has to be heated to different temperatures to give it the required degree of plasticity for rolling or forging into shape, and frequently afterwards reheated or annealed to redistribute stresses produced by working and to induce certain changes in the crystalline structure of the material. In other cases it has to be heated previous to hardening and tempering, and different treatment is required to produce the best results desired in each case. It is, therefore, desirable to get clear ideas as to the object of each of the above operations.

Annealing.—The object of annealing is to redistribute and remove as far as possible all internal stresses in the material induced by rolling, forging, or any other kind of work, and to bring the metal into the best physical state to resist fracture under sudden stress. Annealed steels should possess the

maximum degree of ductility and softness to the file, combined with the highest possible elastic limit. Annealing may therefore be defined as the heat treatment, preferably in a reducing or neutral atmosphere, which produces the maximum amount of ductility, combined with the highest elastic limit. The particular temperature to which a steel must be heated will vary with the Carbon content.

Hardening.—It has already been pointed out in Chap. xv. that when steel containing over ·2 or ·25 of Carbon is suddenly cooled by quenching in water or other media, the steel becomes hard, the hardness varying with the percentage of Carbon present, and within certain limits with the temperature from which the steel is cooled, and the rapidity of cooling. If heated and quenched from too high a temperature the steel will be liable to be brittle, and if from too low a temperature it will not be sufficiently hardened. In hardening, one should therefore aim at heating the steel to the particular temperature, and suddenly cooling it by quenching in water or other medium which will confer the maximum degree of hardness which the particular grade of steel is capable of acquiring.

Tempering.—The hardness conferred upon steel by rapid quenching is not suitable for many industrial purposes, and has to be modified or "tempered" to suit the particular requirements of the case. This may be done by reheating the hardened steel to different temperatures. The operation of tempering may therefore be defined as the modifying of the degree of hardness conferred upon steel by quenching, by heating to certain definite temperatures, followed by slow or rapid cooling. Tempering reduces the brittleness and the hardness, and considerably increases the toughness and ductility of the material, and by varying the conditions of heat treatment almost any required degree of hardness may be produced.

Many years ago Brinell investigated the relation of the structure of steel to its physical properties as influenced by heat treatment, and came to the conclusion that the finer the structure the stronger the steel, and that the object of heat treatment should therefore be to obtain as fine a structure as possible. Brinell made an exhaustive series of experiments on a steel containing ·5 per cent of Carbon, and found there was a certain definite range of temperature to which it was desirable to heat such steel in order to confer upon it the finest structure, whether the steel was allowed to cool slowly or was quenched from this temperature. This range of temperature he further found was identical with that during which the Carbon changed to or from hardening Carbon. The particular temperature at which the Carbon passes from the *cement* to the *hardening state* is accompanied by a change from a more or less coarse to a very fine or amorphous structure, and this he denoted by the letter W, and the best results in hardening were obtained by heating to this temperature previous to quenching; if this temperature be exceeded the steel will become more crystalline and more or less brittle, and if this temperature is not reached the steel will not fully harden. When the steel is heated to any temperature above W the Carbon is always found in the hardening form.

The temperature at which the reverse change of state of Carbon—viz., from the *hardening* to the *cement form*—has the greatest tendency to take place during cooling, Brinell denoted by the letter V, and this he considered the most suitable for the annealing or softening of steel. When the steel is heated to any temperature between V and W * the Carbon passes from the cement form to hardening Carbon; heating above this temperature does not affect the Carbon condition. On heating to the temperature W or higher the

* If Brinell's point W be taken as the Ac_1 change, it is now recognised that it is necessary to heat above W to convert cement Carbon to hardening Carbon.

steel assumes the same structure, *no matter what its structure before the heating may have been.* This is due to the fact that the complete transition of the cement Carbon into hardening Carbon at W is always accompanied by a change to finest structure, which on further heating again becomes coarse.

On heating to a temperature *below W the structure developed will depend on the structure and Carbon condition before heating.*

The above points, W and V, correspond to the critical points observed during the heating and cooling of steel, respectively known as Ac_1 and Ar_1. Thus, W corresponds to the passage of cement Carbon into hardening Carbon during the heating of steel, which transformation is accompanied by a retardation in the rate of heating indicating an absorption of heat. This temperature, W or Ac_1, is generally about 30° C. higher than V or Ar_1, and often covers a range of 25° to 30° C. The temperature indicated by V corresponds to the recalescent point Ar_1 observed during the slow cooling of steel, during which the Carbon passes from the hardening to the cement form—a change accompanied by a retardation in the rate of cooling, indicating an evolution of heat which is sometimes so considerable as to produce a visible rise of temperature in the steel: this is the well-known recalescent point. It will vary somewhat with the grade of steel, being lowest in higher Carbon steels; in medium and hard steels it is generally situated between about 650° and 700° C., and covers a range of about 20° to 30°, but in softer steels it occurs at a higher temperature, and in practically carbonless steel is hardly perceptible at all.

From Brinell's experiments, then, it appears that, to obtain the best results in hardening, steel should be heated about 30° C. above the recalescent point Ar_1 before quenching, and, for annealing, to above the recalescent point but below W.

In 1899* Sauveur, in a paper before the Iron and Steel Institute, gave a most complete summary of the structural changes induced by heat treatment in Carbon steels as revealed by the microscope, which is so concise and clear that it is given *in extenso* as a series of propositions, especially as it practically includes and confirms the most essential points in Brinell's results.

Changes of Structure Brought about by Heat Treatment.

"1. When a piece of steel, hardened or unhardened, is heated to the temperature W, all previous crystallisation, however coarse or however distorted by cold work, is obliterated and replaced by the finest structure which the metal is capable of assuming,† the structure of burnt steel, which cannot be effaced by such treatment, being the only exception.

"2. When a piece of steel, hardened or unhardened, after being heated to the temperature W, is allowed to cool slowly, it retains the fine amorphous-like structure which it had acquired at that temperature. It possesses then the finest structure which unhardened steel is capable of assuming.

"3. When a piece of steel, hardened or unhardened, after being heated to the temperature W, is suddenly cooled from that temperature—by quench-

* *Iron and Steel Inst. Journ.*, 1899, vol. ii.

† It has been stated by Coffin that in the case of soft steel (containing ·2 per cent. of Carbon) a single heating to W breaks up only partially a pre-existing coarse crystallisation, a second reheating to that temperature being necessary to obliterate it altogether. This point should be further investigated. Some steel castings also are said to require more than one heating to W to assume the finest possible structure.

ing it in cold water, for instance—it is fully hardened,* and retains the fine amorphous-like structure acquired at that temperature. The metal possesses then the finest structure which hardened steel is capable of assuming.

"4. When a piece of steel, hardened or unhardened, is heated to a temperature above W and allowed to cool slowly and undisturbedly, the metal, whose crystallisation had been obliterated by its passage through W, crystallises again, the crystals or grains increasing in size until the temperature V is reached, below which there is no further growth.

"*Corollary to* 3 *and* 4.—When a piece of steel, after being heated to a temperature above W, is allowed to cool to W, and then quenched, it will be fully hardened, but its structure will be coarser than if it had been quenched from W without having been previously heated above that temperature.

"5. The higher the temperature above W from which the steel is allowed to cool undisturbedly, the larger the grains.

"6. The slower the cooling from a temperature above W, the larger the grains.

"*Corollary to* 5 *and* 6.—Pieces of steel finished at a temperature above W will have a coarser grain in those parts which have been finished hottest, and where subsequent cooling has been more gradual—*i.e.*, the central portions, or portions further away from the cooling surfaces.

"7. When a piece of steel, hardened or unhardened, is heated to a temperature above W and suddenly cooled, it is fully hardened, but its structure will be coarser than when quenched after having been heated to W.

"8. When a piece of unhardened steel is heated to a temperature below W and quenched or slowly cooled from that temperature, no change takes place in its structure.

"9. When a piece of hardened steel is heated to a temperature below W, some of its hardening Carbon is changed spontaneously into cement Carbon, and the metal is thereby softened. The tendency of the hardening Carbon to pass into the cement condition increases with the temperature, and is the greatest at the temperature W. This transformation, however, is not accompanied by any change in the dimensions of the grains.

"These propositions are for the most part illustrated in fig. 259 in which I have adopted Brinell's mode of representation."

As referred to below, Stead has shown that large or coarse crystallisation is developed in steel containing ·11 Carbon or less by prolonged heating below W, and proposition 8 is, therefore, true only of steels containing over ·2 of Carbon.

Brinell, as the result of experiments with ·75 Carbon steel, came to the conclusion that not only will the hardening Carbon in a piece of steel, previously hardened by quenching from W, be completely changed to cement Carbon on heating to V, but that the structure will also be as fine as if it had been heated to W. Sauveur agrees as regards the Carbon change at V, but his microscopic examinations show no change in size of

* It is evidently meant here, and in all similar references, that after heating to the above temperature, the steel under consideration will acquire all, or practically all, the hardening power which that particular steel is capable of assuming, no further increase of hardness resulting from quenching at a higher temperature. Its absolute degree of hardness will, of course, depend upon its Carbon-content, rate of cooling, and the presence of other impurities; in the case of the softest steels, the increase of hardness may be very nearly, if not altogether, inappreciable. Very low Carbon steels, moreover, do not seem to acquire, in its entirety, during W, whatever hardening power they possess, it being necessary for that purpose to heat the metal to a higher temperature—*i.e.*, pass the upper retardation.

the grain. Stead has confirmed Sauveur's results in this respect, and it is probable, as suggested by the latter, that the finer appearance of the fracture observed by Brinnel is due to a distortion of the crystals, and that there is no actual change in structure.

Stead,* as the result of a most exhaustive series of experiments on low Carbon steels, found that they became coarsely crystalline on prolonged heating at a temperature between 600° and 750° C., but such crystallisation was not always attended with brittleness. On close annealing tin plate bars for forty-eight hours at 700° C. the crystalline structure was developed, and on repeating the annealing it became more and more marked, many of them fractured readily on bending, and all broke on bending to an angle of 60° and straightening. On reheating these bars to 900° C. and allowing them to cool naturally, they became exceedingly tough, and could be bent backwards and forwards without breaking, and a coarse crystalline layer, developed during the first annealing on the outside of the bar, no longer existed.

Ridsdale has confirmed Stead's results that this brittleness produced in mild steel by prolonged heating at a low temperature is removed on reheating to about 900° C.

Stead considers there are two sorts of weakness in low Carbon steel which tend to make it brittle, one weakness between the grains or crystals, which he calls intergranular weakness, and one due to true cleavage planes through the body of the crystals. It is admitted by all metallurgists that, other things being equal, the finer the grain the tougher the material, and this is largely due to the fact that the grains, as a rule, arrange themselves heretogeneously with their cleavage planes at varying angles to each other, but some exceptional cases of brittleness in fine-grained steel may be due to the crystals being arranged so that their cleavage planes lie in one direction, when we should expect that any sudden shock would tend to produce fracture along this line. Mild steel sheets which have been annealed frequently fracture in certain fixed directions, during stamping, at an angle approximating to 45° to the direction of rolling. The author has frequently had to deal with large quantities of sheets which were perfectly ductile, and could be bent close in certain directions, but invariably failed on stamping by fracturing in straight lines. Stead was the first to point out the connection which invariably exists between the lines of fracture and rolling, and that the fracture was a true cleavage fracture through the crystals. Heating up to 900° C. completely removes this form of brittleness.

Brinell states that in forging fairly high Carbon steel the greatest care should be taken that the temperature does not considerably exceed W, and that the forging should be continued until a temperature of a low red heat is reached to obtain the best results.

Campion† has published the results of a number of experiments on the heat treatment of steels containing from ·1 to ·5 per cent. of Carbon, more especially with reference to annealing, his object being to determine the best conditions to obtain the "highest ductility and mineralogical softness combined with the highest possible elastic limit, accompanied in all cases by fine grained microstructure." Steels possessing the above physical characteristics, he considers, are in best condition for resisting sudden shock, which is the best practical test we have as to the efficiency of the annealing. He particularly emphasises the importance of the length of time of heating in addition to the temperature, and the following may be taken as a short summary of about 180 experiments.

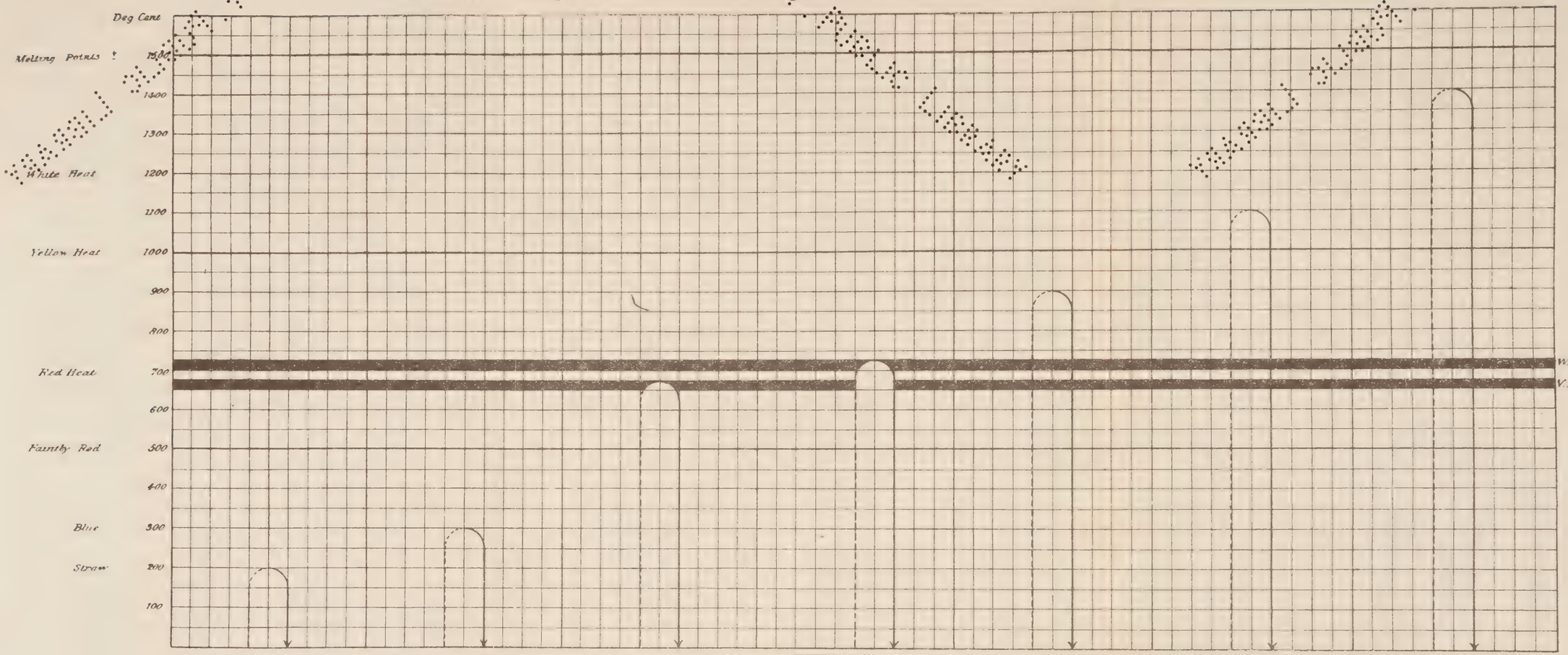
Soft steel, such as is used for constructional purposes and containing

* *Iron and Steel Inst. Journ.*, 1898, vol. ii.

† *West of Scot. Iron and Steel Inst. Journ.*, vol. vii., p. 2, and vol. viii., p. 3.

PLATE XVII.—Changes of Microstructure brought about in Steel by Heat Treatment.

(See page 423.)



Steel originally unhardened. Heated to the Temperatures indicated and	slowly cooled	Structure unchanged.	Structure unchanged.	Structure unchanged.	Previous Structure obliterated and resulting structure		
					Very fine	Less fine	Coarse	Very coarse Burnt
	quenched	Structure unchanged.	Structure unchanged.	Structure unchanged.	Very fine Steel Hardened.	Less fine Steel Hardened.	Coarse Steel Hardened.	Very coarse Steel Hardened.
Steel originally hardened. Heated to the Temperatures indicated and:	slowly cooled or quenched	Some hardening C. changed to Cement C. Dimensions of grains unchanged. High Temper.	More hardening C. changed to Cement C. Dimensions of grains unchanged. Mild Temper.	All hardening C. changed to Cement C. Dimensions of grains unchanged. No Temper left.	Same results as with unhardened Steel.			

Fig. 259.

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about ·15 per cent. of Carbon, appears to be improved in ductility, and to have a finer grain, after being heated to temperatures between 730° and about 850° C. for periods of time varying according to the temperature to which it is raised. If the higher temperature is selected, the pieces must be held there for only a very short time; but he is strongly of opinion that it is unsafe to heat to a higher temperature than about 800° to 820° C. It seems to be an essential condition to obtain a fine-grained microstructure that the piece should be heated as rapidly as possible. He obtained the most satisfactory results by heating rapidly to about 750° C. for a moderate time, and subsequently slowly cooling through the critical range Ar_1, or the V of Brinell, the point at which the transformation from hardening to cement Carbon takes place. The cooling should be fairly rapid until the beginning of Ar_1 is reached (which is between about 710° to 640° C. for soft steel), but should then be as slow as possible, that the transformation of Carbon may be complete.

The metal appears then to possess its maximum amount of ductility, accompanied by fine microstructure, and to be in the most suitable condition to withstand sudden shock. In the case of very soft steel containing, say, ·1 per cent. of Carbon, he found that a single heating to Ac_1, or the W of Brinell, does not always suffice to completely convert the hardening to cement Carbon, and that a second heating to a temperature exceeding V is necessary to give the finest possible grain structure, which confirms a similar statement made by Coffin many years ago.

Heating to a temperature not exceeding Ar_1, or V, he finds, does not produce a fine-grained microstructure, but a prolonged heating at the temperature Ar_1, or V, will effect the complete transformation of the hardening to cement Carbon, with practically no alteration in the size of the grains. This is true of all steels, excepting very soft steels and practically Carbonless iron, which may (as Stead and Ridsdale have shown), on prolonged heating between 600° and 700° C., develop a very coarsely crystalline structure, and produce great brittleness of the metal. This confirms Sauveur's results.

In the case of steel containing about ·35 per cent. Carbon, Campion found the limits of temperature to which the metal should be heated are less wide, apparently the maximum is 800° C., and that for only a very short time; heating for a moderate time at about 700° to 720° C. seems to give the best results.

The steel with ·44 per cent. Carbon gave good results when heated between 620° and 720° C. He is of the opinion that the most suitable temperature for this grade of steel is about 660° C., but much more work is necessary before anything can be definitely stated on this point.

The results of experiments on heating for several hours between 600° and 700° C. seem to confirm the results obtained by other experimenters, that a prolonged heating *below* the critical point Ar_1 does not produce the detrimental effects which it does in the case of soft steels.

The question of the heat treatment of mild steel has also formed the subject of a very complete investigation by Professor Heyn,* the ductility of the material being tested by bending tests, and his experiments, although confirming those of other investigators in many respects, in some give different results. He finds that the fracture of overheated mild steel generally shows a coarse grain, although this is not necessarily always the case, and depends upon the rate of cooling. The structure of overheated steel usually shows large ferrite crystals, but he does not consider such structure a proof that overheating has taken place, as the same structure

* *Iron and Steel Inst. Journ.*, 1902, vol. ii.

may be produced by prolonged heating between 700° and 890° C., although such structure is not necessarily accompanied by brittleness.

When mild steel is annealed at temperatures above 1,000° C., the brittleness of the material is increased if the annealing period is sufficiently long, and the higher the temperature the sooner this brittleness increases and manifests itself. Within certain limits it is possible to produce almost any desired degree of brittleness by varying the temperature and time of annealing. Between 1,100° and 900° C. there exists a definite "temperature limit," *above which*, if annealing is carried on for a longer time at an increasing temperature, the degree of brittleness increases, but *below this limit* brittleness *does not increase*. Overheating not only occurs at an extreme white heat, but becomes apparent at much lower temperatures, provided such temperature exceeds the "temperature limit," and its effects are more marked the longer the period of heating. Professor Heyn differs from Stead and other investigators as to the effect of prolonged annealing at low temperatures, as, according to his results, not only is there no increase in brittleness, but it may actually be decreased by heating for long periods between 700° and 890° C., whereas Stead found low Carbon steel was made extremely brittle by heating between 600° and 750° C.

He confirms Stead's results that the brittleness induced by overheating mild steel can be eliminated by annealing at 900° C., and that the short period of half an hour is sufficient to produce this result, and longer annealing should be avoided. Below 800° C. annealing for five hours did not remove this brittleness, but it was removed by heating for several days at a temperature between 700° and 850° C.

It seems probable that the apparent differences between the results obtained by Stead and Heyn on prolonged annealing, at temperatures under 850° C., are due to some slight variations in the temperatures, as Stead's experiments were made at temperatures of from 600° to 750° C., while Heyn's were at 700° to 890° C. Assuming Stead's samples were heated nearer the lower (600° C.), and Heyn's at or near the higher limit (850° C.), this would be quite sufficient to explain the different results obtained, as we know that mild steel is extremely sensitive to comparatively small variations in heat treatment. Heyn confirms the experience of practical men that mild steel, which has been annealed at a temperature so high that if allowed to cool undisturbed it would be brittle, will exhibit no brittleness when cold, if, while cooling, it has been rolled or forged at a bright red heat.

The influence of work on the size of grain of soft steels has been investigated by Ridsdale,* who states that the size of grain is inversely proportional to the sectional area in normal steels, provided the sections are of such size that they are finished below the critical temperature of Brinell, but not below a dull red heat. This only applies to steels of the same composition, and subjected to similar conditions as to heat treatment. In the same paper Ridsdale gives the results of a large number of experiments on the normal and abnormal heat treatment of various steels, with and without work.

Sauveur † states that steel does not crystallise while it is being worked, and that work above the temperature W has no direct influence upon the structure, but that indirectly, by retarding crystallisation until a lower temperature is reached, it may have a most marked effect. The effect of work at any temperature below a dull red heat is to distort the grains or crystals of the steel, and the lower the temperature the greater the distortion, but such structural deformation, with its accompanying alterations of the

* *Iron and Steel Inst. Journ.*, 1899, vol. ii., p. 113.
† *Ibid.*, 1899, vol. ii.

physical properties of the metal, may be removed by subsequently heating to W.

Brinell's Researches on the Heat Treatment of Steel

Brinell* has carried out an extensive series of experiments on the properties of various classes of steel when subjected to different treatments. Some of his results, and the general conclusions to be drawn from his work, are given here: for more detailed information the original paper by Mr. Axel Wahlberg should be consulted.

The steel used was acid open hearth steel, made at the Fagersta works. From the table of chemical composition it will be seen that, with one exception, the percentage of Silicon is unusually high, and this limits the application of his results, as for many purposes such steels would not generally be used. The entire series of mechanical tests were made by Mr. Axel Wahlberg.

TABLE XCIII.—Chemical Composition.

	Carbon.	Silicon.	Sulphur.	Phosphorus.	Manganese.
	Per cent.	Per cent.	Per cent.	Per cent.	Per cent.
1	0·09	0·005	0·020	0·026	0·10
2	0·16	0·453	0·010	0·030	0·26
3	0·25	0·299	0·012	0·029	0·41
4	0·34	0·266	0·015	0·026	0·49
5	0·44	0·275	0·018	0·029	0·46
6	0·65	0·275	0·011	0·028	0·49
7	0·79	0·378	0·011	0·029	0·20
8	0·94	0·289	0·013	0·025	0·25
9	1·17	0·313	0·010	0·027	0·21

The treatment to which the steels were subjected before testing was as follows:—

I. Hot rolled with no further treatment (normal or untreated).
II. Annealed at 350°, 750°, 850°, 1,000°, 1,100°, and 1,200° C., with subsequent slow cooling.
III. Quenched from 750°, 850°, and 1,000° C., in water.
IV. Quenched from 750°, 850°, and 1,000° C., in oil.
V. Quenched from 750°, 850°, and 1,000° C., in lead.
VI. The test bars quenched in water were subsequently reheated to 350°, 550°, and 650° C.

The oil-quenched bars were reheated to 350° and 500° C. The temperature of the water was 20° C., of the oil 80° C., and of the lead 550° C.

The tests were carried out on bars, 18 millimetres in diameter (·708 in.), and the elongations were measured on 180 millimetres (7·08 ins.)

Annealing with subsequent Slow Cooling.—The general effect of annealing is to increase the elastic limit and ductility without any great alteration in the ultimate stress, but the results are somewhat irregular, and vary with the composition of the steel and the temperature.

Annealing at 350° C. causes a marked rise in the elastic limit, and this rise is somewhat greater as the proportion of Carbon in the material increases. For the softest steel it is almost imperceptible. Above ·34 per cent. of Carbon

* *Iron and Steel Inst. Journ.*, 1901, vol. ii., p. 234.

the ultimate stress and elastic limit increases, while the elongation, although showing a tendency to increase, remains practically constant. At 750° C. there is a further increase in the ductility, accompanied by a tendency to fall in the elastic limit and ultimate stress, especially in medium and high Carbon materials. Annealing at 850° C. causes practically no alteration in the elastic limit in steel containing ·34 per cent. and less of Carbon, but the ductility is slightly greater than in the untreated state. Steels higher than this in Carbon show a marked increase in the elastic limit and elongation. At 1,000° C. the elastic limit on the whole reaches the highest point that is obtained by annealing these samples and the elongation is improved, though for the higher Carbon steels it is not so great as at 850° C. The ultimate stress is not appreciably affected. As would be expected, the quality of the steel shows a tendency to deteriorate when heated to temperatures as high as 1,100° or 1,200° C. Detailed results are given in the following table :—

TABLE XCIV.—ANNEALING.

Carbon per cent.	Ultimate Stress in Tons per Square Inch.					Elastic Limit in Tons per Square Inch. *					Elongation per cent.				
	Annealing Temperatures.														
	Normal.	350° C.	750° C.	850° C.	1000° C.	Normal.	350° C.	750° C.	850° C.	1000° C.	Normal.	350° C.	750° C.	850° C.	1000° C.
0·09	20·7	20·5	20·9	21·5	21·1	9·4	11·2	10·6	9·2	14·0	26·1	36·0	34·3	33·6	36·3
0·16	29·2	28·3	29·4	27·4	29·9	13·0	16·2	15·9	13·7	17·9	27·2	28·8	30·5	29·0	30·9
0·25	33·0	31·5	30·3	31·5	33·8	13·1	16 2	15·0	13·2	19·1	24·6	26·2	28·3	27·1	26·1
0·34	35·0	34·9	33·4	34·3	36·4	11·9	16·2	15·6	13·8	19·1	23·6	25·6	25·3	26·2	25·9
0·44	41·3	43·8	40·9	40·9	41·7	16·2	18·7	16·9	21·4	21·6	18·9	19·5	21·2	23·8	21·6
0·65	54·4	55·9	51·2	56·3	58·5	18·0	23·0	18·7	25·0	24·2	10·6	11·6	15·0	13·8	12·3
0·79	56·9	60·1	55·4	58·3	59·9	20·0	24·4	21·9	25·1	28·0	10·0	10·8	12·1	12·5	12·2
0·94	62·3	64·9	59·8	58·3	68·3	21·9	27·5	20·0	25·7	30·5	6·7	8·5	10·6	13·4	8·4
1·17	56·2	64·3	60·7	55·8	65·9	22·5	31·2	29·4	25·6	35·4	2·6	3·6	9·8	15·1	4·1

* These are the true elastic limits; they must not be confused with the yield points usually taken in commercial testing, which would be from 2 to 3 tons per square inch higher, and in some cases even more than this.

Quenching from 750° C. in water does not cause any notable increase in the ultimate stress for steels containing more than ·16 per cent. of Carbon, and for steel No. 5 (Carbon = ·44) there is a fall in this respect. The elastic limit drops in all steels, and the elongation is nearly constant except for the steels with less than ·44 per cent. of Carbon in which it is lower. On reheating to 350° C. the ultimate stress is about the same as in the untreated bar, and the elongation also recovers; the elastic limit is not restored unless the temperature be raised to 550° C. Generally, there is very little alteration in ultimate stress, &c., by quenching steel from 750° C., whether it be subsequently reheated or not.

Quenching from 850° C. in water causes a decided increase in the ultimate stress in all steels containing ·44 per cent. or less of Carbon. The bars containing ·65 per cent. and ·79 per cent. of Carbon broke prematurely and no test was possible. In the case of the steel containing ·94 per cent. of Carbon the ultimate stress fell, and for steel No. 9 (Carbon = 1·17 per cent.) the test failed. In every case where the test was successful the elongation fell, the loss being greater for high Carbon steels. This is the reverse of the results obtained on quenching from 750° C., at which temperature the four softer steels show the greatest loss of ductility. The elastic limit falls except for steel No. 1 (Carbon = ·09 per cent.), No. 4 (Carbon = ·34 per cent.), and No. 8 (Carbon = ·94 per cent.) In the case of No. 4

(Carbon = ·34 per cent.) the elastic limit is raised very slightly; in the other two it is unaffected.

On reheating to 350° C., steel containing ·16 per cent. of Carbon is practically unchanged, and is inferior to the normal or untreated steel in all properties except ultimate stress. Steels containing from ·25 to ·44 per cent. of Carbon show an increase in ultimate stress and in elastic limit, compared with the quenched samples, but the elongation does not recover. The tests failed from No. 6 (Carbon = ·65 per cent.) to No. 8 (Carbon = ·94 per cent.), and the highest Carbon steel was so brittle as to be useless, though the strength and elasticity were high. Steel containing only ·09 per cent. of Carbon differs from the others in undergoing a further loss in elastic limit on reheating at 350° C., and also in ultimate stress, though this is slightly higher than in the untreated specimen. On reheating to 550° C. the high ultimate stress produced by hardening is *not* reduced, and, with the exception of the two lowest Carbon steels, is not only higher than in the normal steels, but than in those quenched at 850° C. without reheating, a most unexpected result; the elastic limit and contraction of area are both increased, and are greater than in the normal steels, and the elongation is largely restored. The softest steel of the series gains in elastic limit and elongation, and the ultimate stress, though lower than in the hardened bar, is higher than in the normal steel.

There is no advantage in increasing the annealing temperature to 650° C. except in steels containing ·94 per cent. or more of Carbon. For the others the elastic limit is not so high as on reheating to 550° C., and the elongation is still comparatively low. In the case of the two hardest steels there is an increase in the ductility and elastic limit, though at the expense of the ultimate stress.

From these experiments on water hardening it will be found that the *greatest improvement, as shown by tensile tests, is obtained by quenching in water from* 850° *C. and subsequent reheating to* 550° *C.*

Quenching from 1,000° C. in water is comparatively without effect on the elastic limit of steel containing ·09 per cent. Carbon. The ductility falls, but recovers on reheating to 350° C., and at 550° C. rises above its original value. Steels containing from ·16 to ·34 per cent. deteriorate in all respects, and above these no tests were possible.

On reheating to 350° C. the tests failed for steels of Carbon content ·65, ·94, and 1·17 per cent. For the others, the ultimate stress and elastic limit are high, but the ductility is low. An increase of the temperature to 550° or 650° C. does not restore the ductility, and the ultimate stress and elastic limit fall, though they are higher than in the normal state. Details of results are given in Table **xcv.**

Quenching in Oil.—The general effect of quenching from any temperature in oil heated to 80° C. is to produce an increase in ultimate stress, somewhat less than is caused by quenching in water, without the accompanying loss in the elastic limit. As a general rule this is considerably raised, and the ductility falls.

When quenched from 750° C. in oil all steels have their elastic limit raised, with the exception of No. 5 (·44 per cent. of Carbon), which in all respects is practically the same as in the normal state. Steels containing ·34 per cent. or less of Carbon undergo a loss of ductility, while with ·65 per cent. or more they are improved. The ultimate stress is increased for the two lowest and also for the highest in Carbon; in the others it is unchanged.

Quenching from 950° C. in oil improves the elastic limit of all steels except those containing ·16 and ·25 per cent. of Carbon, which are somewhat deter-

TABLE XCV.—Water Quenching.

Carbon per cent.	Ultimate Stress in Tons per Square Inch.						Elastic Limit in Tons per Square Inch.						Elongation per cent.					
	Temperature of Quenching.																	
	Normal.	750° C.	750° C. reheated to 550° C.	850° C.	850° C. reheated to 550° C.	850° C. reheated to 650° C.	Normal.	750° C.	750° C. reheated to 550° C.	850° C.	850° C. reheated to 550° C.	850° C. reheated to 650° C.	Normal.	750° C.	750° C. reheated to 550° C.	850° C.	850° C. reheated to 550° C.	850° C. reheated to 650° C.
0·09	20·7	35·8	20·6	39·2	22·7	21·9	9·4	8·7	11·2	11·3	13·8	11·3	26·1	15·6	34·9	15·8	30·9	33·1
0·16	29·2	36·2	28·0	49·0	35·2	32·7	13·0	8·1	15·0	10·7	13·8	10·5	27·2	14·6	28·8	7·5	22·1	12·9
0·25	33·0	37·3	30·8	46·6	50·1	41·4	13·1	9·9	15·0	9·7	31·4	22·6	24·6	19·6	27·5	5·8	10·0	15·3
0·34	35·0	39·2	34·1	57·6	56·8	44·6	11·9	9·9	13·7	11·2	26·4	21·2	23·6	19·2	24·4	1·3	10·8	12·7
0·44	41·3	35·2	40·7	55·8	69·6	52·2	16·2	12·5	16·2	8·7	41·4	31·4	18·9	17·5	19·6	0·3	9·8	13·3
0·65	54·4	54·4	52·0	No test.	75·7	57·9	18·0	14·9	19·9	No test.	51·4	35·1	10·6	13·2	15·6	No test.	7·4	11·6
0·79	56·9	58·1	55·8	,,	79·5	60·7	20·0	11·3	21·2	,,	62·7	43·8	10·0	11·5	13·1	,,	7·2	10·6
0·94	62·3	63·1	63·9	61·0	84·0	63·6	21·9	20·0	21·3	22·5	39·9	48·6	6·7	6·2	10·4	0·0	6·4	9·7
1·17	56·2	63·7	62·5	No test.	89·7	65·8	22·5	16·3	26·3	No test.	41·1	49·1	2·6	3·9	5·6	No test.	5·8	8·3

The comparatively small hardening effect on quenching from 750° C. is probably due to the steels being more or less impure, also to the size of the bars. The original statement by Brinell, confirmed by Sauveur's microscopic work, that the maximum degree of hardness which a given steel is capable of taking is conferred by quenching from W (*e.g.*, about 750° C.), is only true of pure steels and VERY SMALL SECTIONS when chilling effect can act almost instantaneously.

iorated. The ultimate stress is raised in all, and the ductility falls except in the two hardest steels.

Quenching from 1,000° C. in oil raises the ultimate stress and elastic limit in all cases. The ductility is lowered except in the softest and the two hardest steels.

Steels quenched from 750° C. in oil and reheated to 350° or 550° C. lose the increased ultimate stress produced by the hardening, and do not differ appreciably from the normal steel in this respect. The elastic limit is sometimes further increased and sometimes lowered, but it is generally higher than in the normal state. The elongation is also higher than in the normal steels, or than in the hardened material except for ·79 per cent. of Carbon and above, when it remains constant. The hardest steel (Carbon = 1·17 per cent.) is unaffected in any way by reheating.

Reheating to 350° C. produces no further change in the ultimate stress in steel *quenched in oil from 850° C.*, with the exception of the two softest varieties, in which case there is a fall, though they show an increase over the normal specimen. The elastic limit is higher than in the normal state except for No. 3 (Carbon = ·25 per cent.), when it is constant, and No. 2 (Carbon = ·16 per cent.), in which it is slightly less. The ductility is lowered except in the softest and in the two hardest materials.

The results on reheating at 550° C. are much the same as those obtained at 350° C.

Reheating at 350° or 550° C. does not restore the loss in ductility caused by oil quenching at 1,000° C., and, as a rule, no change is produced. The ultimate stress remains nearly the same as in the hardened steels, and the same statement holds good for the elastic limit, except in steels containing ·25 per cent. or less of Carbon, which are slightly improved. Some detailed results are given in the following table :—

TABLE XCVI.—Oil Quenching.

Carbon per cent.	Ultimate Stress in Tons per Square Inch.			Elastic Limit in Tons per Square Inch.			Elongation per cent.		
	Temperature of Quenching.								
	Normal.	Quenched at 750° C., Reheated to 550° C.	Quenched at 850° C., Reheated to 550° C.	Normal.	Quenched at 750° C., Reheated to 550° C.	Quenched at 850° C., Reheated to 550° C.	Normal.	Quenched at 750° C., Reheated to 550° C.	Quenched at 850° C., Reheated to 550° C.
0·09	20·7	20·5	22·5	9·4	12·5	12·5	26·1	35·1	34·9
0·16	29·2	27·7	32·1	13·0	13·7	11·3	27·2	28·8	27·8
0·25	33 0	31·7	40·6	13·1	13·8	19·9	24·6	26·9	17·1
0·34	35·0	33·8	45·9	11·9	16·2	27·5	23·6	25·0	17·8
0·44	41·3	39·5	56·2	16·2	16·2	32·4	18·9	21·7	13·1
0·65	54·4	50·5	74·8	18·0	19·9	41·2	10·6	13·3	10·6
0·79	56·9	56·7	79·9	20·0	21·8	48·9	10·0	12·6	8·0
0·94	62·3	58·9	86·1	21·9	24·9	32·8	6·7	10·2	5·8
1·17	56·2	62·3	83·2	22·5	27·5	34·5	2·6	8·6	4·0

Lead Hardening.—*Hardening from 750° C. in lead* is practically without effect on any steel except the hardest, in which ultimate stress, elastic limit, elongation, and contraction are all slightly improved.

Hardening from 850° C. in lead raises the ultimate stress of all steel except the softest, which is unchanged. The elastic limit is unaltered for specimens containing ·09 and ·16 per cent. of Carbon, is lowered with ·25 per cent. of Carbon, and raised for all harder steels. The elongation is generally either unaffected or diminished. As was the case on hardening at 750° C. in lead the hardest steel is improved in all respects.

Hardening from 1000° C. in lead raises the ultimate stress and elastic limit. The elongation is constant or falls.

The following tables show the influence of the different heat treatments on the individual steels :—

TABLE XCVII.—Carbon = ·09 per cent.

	Ultimate Stress per Square Inch.		Elastic Limit per Square Inch.		Elongation per cent.	Contraction per cent.
	Tons.	Lbs.	Tons.	Lbs.	180 mm. = 7·08 ins.	
Normal steel,	20·7	46,700	9·4	21,050	26·1	73·3
Annealed at 350° C.,	20·5	45,900	11·2	25,080	36·0	75·0
,, 750° C.,	20·9	46,800	10·6	23,700	34·3	73·8
,, 850° C.,	21·5	48,160	9·2	20,600	33·6	73·6
,, 1,000° C.,	21·1	47,260	14·0	31,360	36·3	77·4
Water quenched at 750° C.,	35·8	80,200	8·7	19,500	15·6	54·0
,, ,, reheated to 550° C.,	20·6	46,100	11·2	25,100	34·9	76·6
Water quenched at 850° C.,	39·2	87,800	11·3	25,300	15·8	65·5
,, ,, reheated to 550° C.,	22·7	50,800	13·8	30,900	30·9	75 0
,, ,, ,, 650° C.,	21·9	49,060	11·3	25,300	33·1	76·0
Oil quenched at 750° C. and reheated to 550 C°.,	20·5	45,900	12·5	28,000	35·1	77·8
Oil quenched at 850° C. and reheated to 550° C.,	22·5	50,400	12·5	28,000	34·9	74·9

TABLE XCVIII.—Carbon = ·16 per cent.

	Ultimate Stress per Square Inch.		Elastic Limit per Square Inch.		Elongation per cent.	Contraction per cent.
	Tons.	Lbs.	Tons.	Lbs.	180 mm. = 7·08 ins.	
Normal steel,	29·2	65,400	13·0	29,100	27·2	61·3
Annealed at 350° C.,	28·3	63,400	16·2	36,300	28·8	61·9
,, 750° C.,	29·4	65,860	15·9	35,600	30·5	60·3
,, 850° C.,	27·4	61,400	13·7	30,760	29·0	58·9
,, 1,000° C.,	29·9	67,000	17·9	40,090	30·9	65·2
Water quenched at 750° C.,	36 2	81,180	8·1	18,144	14·6	50·2
,, ,, reheated to 550° C.,	28·0	62,700	15·0	33,600	28·8	65·1
Water quenched at 850° C.,	49·0	109,800	10·7	24,000	7·5	47·4
,, ,, reheated to 550° C.,	35·2	78,800	13·8	30,900	22·1	63·8
,, ,, ,, 650° C.,	32·7	73,200	10·5	23,500	22·9	67·4
Oil quenched at 750° C. and reheated to 550° C.,	27·7	62,000	13·7	30,700	28·8	61·3
Oil quenched at 850° C. and reheated to 550° C.,	32·1	71,900	11·3	25,300	27·8	62·6

TABLE XCIX.—Carbon = ·25 per cent.

	Ultimate Stress per Square Inch.		Elastic Limit per Square Inch.		Elongation per cent.	Contraction per cent.
	Tons.	Lbs.	Tons.	Lbs.	180 mm. = 7·08 ins.	
Normal steel,	33·0	73,900	13·1	29,300	24·6	50·9
Annealed at 350° C.,	31·5	70,560	16·2	36,300	26·2	57·7
,, 750° C.,	30·3	67,900	15·0	33,600	28·3	58·9
,, 850° C.,	31·5	70,560	13·2	29,600	27·1	50·7
,, 1,000° C.,	33·8	75,700	19·1	42,800	26·1	50·7
Water quenched at 750° C.,	37·3	83,500	9·9	22,200	19·6	53·3
,, ,, reheated to 550° C.,	30·8	69,000	15·0	33,600	27·5	59·1
Water quenched at 850° C.,	46·6	104,400	9·7	21,700	5·8	14·3
,, ,, reheated to 550° C.,	50·1	112,200	31·4	70,300	10·0	50·3
,, ,, ,, 650° C.,	41·4	92,700	22·6	50,600	15·3	58·2
Oil quenched at 750° C. and reheated to 550° C.,	31·7	71,000	13·8	30,900	26·9	56·9
Oil quenched at 850° C. and reheated to 550° C.,	40·6	90,900	19·9	44,600	17·1	54·8

TABLE C.—Carbon = ·34 per cent.

	Ultimate Stress per Square Inch.		Elastic Limit per Square Inch.		Elongation per cent.	Contraction per cent.
	Tons.	Lbs.	Tons.	Lbs.	180 mm. = 7·08 ins.	
Normal steel,	35·0	78,400	11·9	26,650	23·6	53·2
Annealed at 350° C.,	34·9	78,200	16·2	36,300	25·6	54·8
,, 750° C.,	33·4	74,800	15·6	34,900	25·3	54·7
,, 850° C.,	34·3	76,800	13·8	30,900	26·2	53·7
,, 1,000° C.,	36·4	81,500	19·1	42,800	25·9	57·5
Water quenched at 750° C.,	39·2	87,800	9·9	22,200	19·2	51·7
,, ,, reheated to 550° C.,	34·1	76,400	13·7	30,700	24·4	54·8
Water quenched at 850° C.,	57·6	129,000	11·2	25,100	1·3	4·1
,, ,, reheated to 550° C.,	56·8	127,200	26·4	59,100	10·8	59·6
,, ,, ,, 650° C.,	44·6	99,900	21·2	47,500	12·7	63·2
Oil quenched at 750° C. and reheated to 550° C.,	33·8	75,700	16·2	36,300	25·0	54·7
Oil quenched at 850° C. and reheated to 550° C.,	45·9	102,800	27·5	61,600	17·8	56·2

TABLE CI.—Carbon = ·44 per cent.

	Ultimate Stress per Square Inch.		Elastic Limit per Square Inch.		Elongation per cent.	Contraction per cent.
	Tons.	Lbs.	Tons.	Lbs.	180 mm. = 7·08 ins.	
Normal steel,	41·3	92,500	16·2	36,300	18·9	42·8
Annealed at 350° C.,	43·8	98,100	18·7	41,900	19·5	38·7
,, 750° C.,	40·9	91,600	16·9	37,850	21·2	47·6
,, 850° C.,	40·9	91,600	21·4	47,900	23·8	45 8
,, 1,000° C.,	41·7	93,400	21·6	48,400	21·6	48·3
Water quenched at 750° C.,	35·2	78,800	12·5	28,000	17·5	41·1
,, ,, reheated to 550° C.,	40·7	91,200	16·2	36,300	19·6	44·4
Water quenched at 850° C.,	55·8	125,000	8·7	19,500	0·3	2·5
,, ,, reheated to 550° C.,	69·6	155,900	41·4	92,700	9·8	55·3
,, ,, ,, 650° C.,	52·2	116,900	31·4	70,300	13·3	58·9
Oil quenched at 750° C. and reheated to 550° C.,	39·5	88,500	16·2	36,300	21·7	57·2
Oil quenched at 850° C. and reheated to 550° C.,	56·2	125,900	32·4	72,600	13·1	49·4

TABLE CII.—CARBON = ·65 PER CENT.

	Ultimate Stress per Square Inch.		Elastic Limit per Square Inch.		Elongation per cent.	Contraction per cent.
	Tons.	Lbs.	Tons.	Lbs.	180 mm. = 7·08 ins.	
Normal steel,	54·4	121,850	18·0	40,300	10·6	24·1
Annealed at 350° C.,	55·9	125,200	23·0	51,500	11·6	21·0
,, 750° C.,	51·2	114,700	18·7	41,900	15·0	26·6
,, 850° C.,	56·3	126,100	25·0	56,000	13·8	30·2
,, 1,000° C.,	58·5	131,000	24·2	54,200	12·3	27·2
Water quenched at 750° C.,	54·4	121,850	14·9	33,400	13·2	21·8
,, ,, reheated to 550° C.,	52·0	116,500	19·9	44,600	15·6	27·7
Water quenched at 850° C.,	Test piece broke prematurely.					
,, ,, reheated to 550° C.,	75·7	169,600	51·4	115,100	7·4	33·9
,, ,, ,, 650° C.,	57·9	129,700	35·1	78,600	11·6	41·8
Oil quenched at 750° C. and reheated to 550° C.,	50·5	113,100	19·9	44,600	13·3	24·9
Oil quenched at 850° C. and reheated to 550° C.,	74·8	167,550	41·2	92,300	10 6	41·5

TABLE CIII.—CARBON = ·79 PER CENT.

	Ultimate Stress per Square Inch.		Elastic Limit per Square Inch.		Elongation per cent.	Contraction per cent.
	Tons.	Lbs.	Tons.	Lbs.	180 mm. = 7·08 ins.	
Normal steel,	56·9	127,450	20·0	44,800	10·0	14·8
Annealed at 350° C.,	60·1	134,600	24·4	54,650	10·8	14·7
,, 750° C.,	55·4	124,100	21·9	49,050	12·1	20·6
,, 850° C.,	58·3	130,600	25·1	56,200	12·5	24·5
,, 1,000° C.,	59·9	134,200	28·0	62,700	12·2	21·3
Water quenched at 750° C.,	58·1	130,100	11·3	25,300	11·5	16·8
,, ,, reheated to 550° C.,	55·8	125,000	21·2	47,500	13·1	29·6
Water quenched at 850° C.,	Test piece broke prematurely.					
,, ,, reheated to 550° C.,	79·5	178,100	62·7	140,400	7·2	27·4
,, ,, ,, 650° C.,	60·7	136,000	43·8	98,100	10·6	53·4
Oil quenched at 750° C. and reheated to 550° C.,	56·7	127,000	21·8	48,800	12·6	18·9
Oil quenched at 850° C. and reheated to 550° C.,	79·9	179,000	48·9	109,500	8·0	28·5

TABLE CIV.—CARBON = ·94 PER CENT.

	Ultimate Stress per Square Inch.		Elastic Limit per Square Inch.		Elongation per cent.	Contraction per cent.
	Tons.	Lbs.	Tons.	Lbs.	180 mm. = 7·08 ins.	
Normal steel,	62·3	139,550	21·9	49,050	6·7	8·5
Annealed at 350° C.,	64·9	145,400	27·5	61,600	8·5	10·7
,, 750° C.,	59·8	133,900	20·0	44,800	10·6	15·7
,, 850° C.,	58·3	130,600	25·7	57,600	13·4	23·6
,, 1,000° C.,	68·3	153,000	30·5	68,300	8·4	11·1
Water quenched at 750° C.,	63·1	141,300	20·0	44,800	6·2	12·7
,, ,, reheated to 550° C.,	63·9	143,100	21·3	47,700	10·4	12·7
Water quenched at 850° C.,	61·0	136,600	22·5	50,400	nil.	nil.
,, ,, reheated to 550° C.,	84·0	188,200	39·9	89,400	6·4	14·9
,, ,, ,, 650° C.,	63·6	142,460	48·6	108,860	9·7	35·1
Oil quenched at 750° C. and reheated to 550° C.,	58·9	131,900	24·9	55,800	10·2	15·9
Oil quenched at 850° C. and reheated to 550° C.,	86·1	192,800	32·8	73,500	5·8	12·5

TABLE CV.—Carbon = 1·17 per cent.

	Ultimate Stress per Square Inch.		Elastic Limit per Square Inch.		Elongation per cent.	Contraction per cent.
	Tons.	Lbs.	Tons.	Lbs.	180 mm. = 7·08 ins.	
Normal steel, ...	56·2	125,900	22·5	50,400	2·6	4·2
Annealed at 350° C., . . .	64·3	144,000	31·2	69,900	3·6	4·3
,, 750° C., . . .	60·7	135,960	29·4	65,850	9·8	12·5
,, 850° C., . . .	55·8	125,000	25·6	57,400	15·1	24·8
,, 1,000° C., . . .	65·9	147,680	35·4	79,300	4·1	4·0
Water quenched at 750° C., . .	63·7	142,680	16·3	36,500	4·9	6·3
,, ,, reheated to 550° C.,	62·5	140,000	26·3	58,900	5·6	6·3
Water quenched at 850° C., . .	Test piece broke prematurely.					
,, ,, reheated to 550° C.,	89·7	200,900	41·1	92,060	5·8	10·9
,, ,, ,, 650° C.,	65·8	147,400	49·1	110,000	8·3	29·8
Oil quenched at 750° C. and reheated to 550° C., . .	62·3	139,500	27·5	61,600	8·6	9·6
Oil quenched at 850° C. and reheated to 550° C., . .	83·2	186,400	34·5	77,300	4·0	11·4

Impact Tests.—Mr. Axel Wahlberg at the same time carried out a series of impact tests on the steels at temperatures of 30° and −26° C. The previous treatment of the steel was as follows:—

I. Hot rolled without further treatment (normal).

II. Annealed at 350°, 650°, 750°, 850°, 1,000°, and 1,200° C., with subsequent slow cooling.

III. Heated to 850° C. and quenched—

(*a*) In water at 20° C. with subsequent reheating to 550° C.

(*b*) In oil at 80° C. with subsequent reheating to 550° C.

(*c*) In lead heated to 550° C.

The test bars were 30 mm. (1·18 inches) square, and the rolling skin was in all cases left intact. All the bars were nicked on both sides with a saw, the cut being 6 mm. (·236 inch) deep and 1 mm. (·039 inch) in width. For testing, they were fixed horizontally in a heavy anvil block with a portion of the bar (2·16 inches long) projecting beyond the nick, and this projecting portion was struck by a falling weight until the end broke off. The saw cuts or nicks were 2·16 inches apart. In every case two tests were made; one with the bars supported, so that the notches were on the sides, in which case the bars are called "unnotched," and one with the notches on the upper and under surfaces, when the bars are called notched. Though by this means it is possible always to have the same area of fracture, yet, owing to the considerable depth of the saw cuts, it is difficult to compare "unnotched" with notched bars, as in the first case the greater dimension of the area was vertical, and in the second horizontal.

The blows were struck by a freely falling hammer weighing 18 kilos. (39·6 lbs.). The height of the first drop was 100 mm. (3·93 inches), of the second 200 mm., of the third 300 mm., and so on, up to a height of 2,500 mm. (98·4 inches) at the twenty-fifth blow, beyond which the tests were not carried. The total work performed by weight falling 2,500 mm. was 585 metre-kilos., or 4,231 foot-lbs., and is calculated by multiplying the total height through which the hammer has fallen by its weight. The values obtained are not absolute, and serve only to place the steels in their order of resistance to impact. In comparing Brinell's experiments with those of other observers, the rectangular form of the notches should be borne in mind, as V-shaped notches have been found to give very different results.

In the following table are given a few of Brinell's results at a temperature of 30° C.:—

TABLE CVI.—Impact Tests at 30° C. (Brinell).

Number.	Carbon per cent.	Normal.				Annealed at 850° C.				Annealed at 1,000° C.				Water hardened at 850° C., reheated to 550° C.				Oil hardened at 850° C., reheated to 550° C.				Lead hardened at 850° C.			
		Unnotched.		Notched.		Unnotched.		Notched.		Unnotched.		Notched.		Unnotched.		Notched.		Unnotched.		Notched.		Unnotched.		Notched.	
		Blows.	Foot-lbs.	Blows.	Foot-lbs.	Blows.	Foot-lbs.	Blows.	Foot-lbs.	Blows.	Foot-lbs.	Blows.	Foot-lbs.	Blows.	Foot-lbs.	Blows.	Foot-lbs.	Blows.	Foot-lbs.	Blows.	Foot-lbs.	Blows.	Foot-lbs.	Blows.	Foot-lbs.
9.	1·17	5	195	2	39	8	470	4	130	6	274	3	79	9	585	3	79	10	715	4	130	7	361	4	130
8.	0·94	8	470	3	79	7	361	4	130	7	361	4	130	14	1,365	5	195	9	585	5	195	9	585	4	130
7.	0·79	6	274	6	274	6	274	4	130	7	361	5	195	15	1,561	8	470	14	1,365	6	274	8	470	4	130
6.	0·65	8	470	4	130	7	361	4	130	9	585	4	130	16	1,771	6	274	14	1,365	4	130	13	1,184	4	130
5.	0·44	10	715	4	130	11	860	5	195	11	860	5	195	16	1,771	8	470	16	1,771	6	274	13	1,184	6	274
4.	0·34	13	1,184	5	195	13	1,184	6	274	12	1,012	7	361	16	1,771	8	470	14	1,365	7	361	12	1,012	7	361
3.	0·25	16	1,771	5	195	12	1,012	7	361	15	1,561	10	715	20	2,732	8	470	17	1,981	8	470	15	1,561	10	715
2.	0·16	20	2,732	8	470	16	1,771	7	361	20	2,732	12	1,012	19	2,472	11	860	21	3,007	10	715	16	1,771	9	585
1.	0·09	25*	4,231*	4	130	20	2,732	4	130	19	2,472	19	2,472	19	2,472	19	2,472	25*	4,231*	20	2,732	25*	4,231*	4	130

Annealing at 350° and 650° generally lowers the resistance to shock, and on annealing at 750° the bars gave practically the same results as normal bars. The figures for these tests are consequently omitted from the table.

Note.—The steels in this table are arranged in reverse order, the highest Carbon steels being given first.

* Unbroken at the twenty-fifth blow.

General Conclusions.—The following conclusions may be drawn from the complete tables relating to the drop and other tests given in the paper to which reference has already been made.

According to the tensile tests, steel appears to be slightly improved by *annealing to 350° C.*, especially as regards the elastic limit, but the impact tests do not bear this out as the general effect of annealing at either 350° or 650° C. is to lower the resistance of "unnotched bars" to shock. With notched bars the results are more irregular.

On annealing at 750° C. there is a tendency in many cases to return at least to the normal strength, and this tendency is more marked in the case of the notched bars.

At 850° C. "unnotched" bars show, on the whole, a loss of strength, but notched bars are generally improved.

On annealing at 1,000° C. the two softest steels show a loss when tested in the "unnotched" state, but above ·16 per cent. Carbon there is a general improvement, notched bars all gaining in strength.

Annealing at 1,200° C. on the whole leaves the "unnotched" bars unaltered, but improves the notched bars.

Quenching in water from 850° C. and reheating to 550° C. causes a marked improvement in all "unnotched" bars with the exception of the two softest, which are practically unaffected by this treatment. The notched bars are all considerably improved.

Quenching in oil from 850° C. with subsequent reheating to 550° C. improves both "unnotched" and notched bars, but the effect is not so marked as when water is used as the quenching medium.

Hardening in lead from 850° C. generally improves the steels, but the effect is less marked than with oil or water hardening and subsequent reheating.

The effect of notching is to reduce the resistance to impact by about two-thirds. From the experiments carried out at – 26° C. it appears that a low temperature is injurious to all steels, those low in Carbon suffering relatively more than the harder materials.

Brinell, as the result of his earliest experiments, recommended that, to obtain the best results with annealing, steel should be heated to the temperature V and be slowly cooled, but should not be heated to W. The above most exhaustive series of experiments can hardly be said to confirm this, as we find that annealing at 850° C., which is above W, increases the elastic limit and ductility in steels with more than ·34 per cent. Carbon, while the highest elastic limit combined with ductility is obtained in all steel containing less than ·79 per cent. Carbon by heating to 1,000° C.

Annealing at 750° C., which, although rather high for V in most steels, is the temperature nearest to V employed by Brinell in these experiments, while increasing the ductility, fails to increase the elastic limit, except for steels below ·34 Carbon, and consequently does not produce the desired combination of the greatest ductility with the highest elastic limit.

The drop tests also show that the material was not practically improved by this latter treatment. Very probably the question of time plays an important part, and, provided a steel is maintained at 750° for a considerable time, the same physical condition would be induced as by heating for a shorter period at 850° to 900°. Much work has yet to be done in this direction before the best conditions for annealing, both as regards time and temperature for varying classes of steel, can be definitely settled; but, so far as our present knowledge goes, heating to about 800° C. and maintaining the steel at that temperature for a short time, or even at a little higher temperature, say not exceeding 850°, with fairly rapid cooling, appears to give very good results in practical work.

The fact that quenching from 750° C. seems to have had comparatively little effect upon either the ultimate stress, elastic limit, or elongation, and that what alteration there is is less noticeable in the high Carbon steels than in the low, is certainly very remarkable. From Brinell's early experiments and from general experience it would be expected that quenching from such a temperature would have conferred very nearly the maximum degree of hardness the steel was capable of taking, and these results are difficult to explain.*

The bars quenched from 850° C. show a great increase in hardness compared with those quenched from 750° C., some of the higher Carbon steels being so brittle that they broke before the load was fully on the bar. On increasing the quenching temperature to 1,000,° bars with more than ·34 per cent. Carbon were so brittle that tests could not be obtained.

The results obtained by reheating to different temperatures have con firmed those of other experimenters that, although tempering below 350° C. has some effect in removing brittleness, in most cases a higher temperature is required, about 550° C. apparently giving the best results, little being gained by further increasing the temperature.

An important paper on the heat treatment of steel was read before the Iron and Steel Institute at the May meeting, 1903, by Campion,† one of the Carnegie scholars, for which he was awarded the Carnegie gold medal. The results are of great practical utility, as the experiments were made on bars varying from $1\frac{1}{2}$ to 6 inches diameter, and of the same Carbon content, thus showing the influence of mass. It will be seen that the annealing temperature giving the best results varied from 600° to 850° C., according to the composition of the steel and the size of the bars. The following is a summary of the results :—

Small sections of rolled steel containing ·2 per cent. Carbon can be heated between very wide limits of temperature without seriously impairing their power of resisting sudden shock, as shown by results of bending tests. The results of the experiments indicate, however, that 850° C. is the maximum temperature to which such material should be heated.

The rate of cooling to Ar_1 appeared to have considerable influence upon the result; when heated to 800° C. and higher, slow cooling tended to produce brittleness, a fact which probably explains some of those abnormal results often met with in works. In rolling small sections it is the practice in many works to stack the bars on the bank whilst still hot; this means that they are either cooled very slowly through Ar_1, or are kept for a very long time between 500° and 600° C. The experiments point to this as being a dangerous temperature at which to heat the material.

The results obtained with larger sections of rolled steel containing ·2 per cent. Carbon, indicated 800° C. as the maximum temperature at which such material should be heated to obtain it in the most suitable condition to resist sudden shock. This temperature is slightly lower than the maximum obtained for the smaller bars.

The results of the experiments on forged bars of this steel, 6 inches in diameter, indicated 700° to 850° C. as the limits of temperature at which bars of this size should be heated to obtain the maximum resistance to sudden shock. At temperatures between 500° and 650° C. brittleness was produced in a very marked degree, *especially if followed by slow cooling.*

A second set of experiments, carried out with this size of bar, showed very clearly the effect of heating to temperatures between 500° and 1,000° C.,

* It is probable that on quenching from 750° C. the Carbon change is complete only with very small sections, and that for bars of the size used in these experiments (·708 in dia.) a higher temperature is necessary.

† *Iron and Steel Inst. Journ.*, 1903, No. 1.

and the results indicated 800° C. as the best temperature at which to heat bars of this size and composition.

Steel containing about ·3 or ·4 per cent. of Carbon in small rolled sections was improved as regards its shock-resisting qualities when heated to temperatures varying from 650° to 800° C., whether followed by slow or rapid cooling.

Heating between 500° and 600° C. did not produce the brittleness which occurs in ·2 Carbon steel when it is heated under similar conditions.

Large rolled bars of this material gave the best results after heating to temperatures of 700° to 800° C. When heated at 900° C. and higher, a pronounced brittleness developed. Slow cooling did not seem to be very injurious.

Forged bars of this steel, 6 inches in diameter, appeared to be brought into the best condition for resisting sudden shock by heating to temperatures between 700° and 760° C., followed either by slow or rapid cooling. The bar heated to 800° C. showed a marked falling off in the drop-test result, but as only one experiment was made at this temperature, too much reliance must not be placed upon the result, which might be due to accidental causes.

Steel containing ·5 to ·6 per cent. Carbon in small rolled sections appeared to be in its toughest and strongest condition after being heated to from 700° to 800° C., followed by either slow or rapid cooling. The larger rolled bars of this steel seemed to require the same treatment as the 1½-inch bars.

The forged bars required heating to a slightly lower temperature than the rolled bars in order to obtain the best results. The steel containing between ·6 and ·7 per cent. of Carbon in small rolled sections possessed the greatest ductility and resistance to sudden shock, as determined by bend tests, after being heated to from 600° to 700° C. The 4-inch rolled bars of this steel gave the best drop-test results at about 720° C. The rate of cooling apparently did not very much influence the results.

This steel in the forged bars of 6 inches diameter gave the best result under the falling weight test after being heated to 700° to 760° C., and followed by either rapid or slow cooling. Heating this grade of steel in large bars to temperatures of over 850° C. produced brittleness, which was very marked when the temperature exceeded 900° C.

The following table shows the heat treatment which gave the best results with each steel :—

Size of Bar.	Steel containing Carbon.	Temperature giving best results.	Rate of Cooling.	Remarks.
Inches.	Per cent.	° C.		
1½	0·200	650-850	fairly rapid.	Heating to 500° to 600° C. develops brittleness. Very slow cooling deleterious.
4	,,	700-800	,,	Ditto, but very much less pronounced.
6	,,	800-850	,,	Heated to 500° to 600° C. great brittleness develops very easily.
1½	0·350	650-800	,,	.....
4	,,	700-800	,,	Brittle if heated to 900° C. and above.
6	,,	700-760	slow or rapid.	.....
1½	0·550	700-800	,,	Rate of cooling, practically no effect.
4	,,	,,	,,	,, ,,
6	,,	600-760	,,	,, ,,
1½	0·650	600-700	,,	,, ,,
4	,,	about 720	,,	,, ,,
6	,,	700-760	,,	,, ,,

The actual temperature employed for annealing in works varies very considerably, and it is only comparatively recently that exact records of temperatures have been taken; so far as it has been possible to obtain information the best practice seems to be to anneal at about 750° to 850°, which confirms generally the results obtained by experiments on a small scale. Howe* says the best results are obtained by annealing steels with ·12 to 1 per cent. of Carbon at a bright cherry-red, which may be taken as under 900° C., probably not far from 850° C. Campbell carried out experiments on annealing at a dull yellow heat, which is probably about 900° or from that to 1,000° C. The great difficulty in annealing on a commercial scale is the equable heating of large masses of material, and if not conducted with great care it is liable to do more harm than good. Thus, in annealing plates or bars, when a furnace is full, those on the outside are sure to be heated to a higher temperature than those in the centre of the pile, and consequently different results are obtained on heating the same class of material in the same furnace. The latest experimental work having shown that heating for a very short time and rapid cooling is all that is required, may do something to facilitate the annealing of large quantities of material, as, instead of heating very slowly and allowing to remain for a considerable time, it appears to be necessary only to pass the materials rapidly through a furnace, allowing them just time to be heated through and to acquire the full temperature of the furnace. The question of ensuring regular cooling presents also many difficulties, as to get the best results this should be fairly rapid without any local chilling, such as is produced by contact with cold plates, &c.—conditions not easy to carry out in dealing with hundreds of tons of material a day. These difficulties are so well recognised that for most structural steel it is considered safer to take material as it leaves the rolls rather than have it annealed, as, owing to the great difficulties of carrying out the operation on a large scale, there is often considerable risk of damaging rather than improving the steel.

These remarks do not apply to large forgings or castings, which are frequently annealed by themselves in a furnace to which a great deal of personal attention can be given to ensure good results.

The oil quenching results of Brinell and Wahlberg seem broadly to confirm those obtained in ordinary practice, so far as results are available. The usual practice for oil quenching for guns, axles, and similar steels is to heat to a temperature varying from 750° to 850°, most usually about 800°, quench in oil at 20° C., and afterwards reheat to about 550° to 650° C. Some manufacturers never reheat above 350° C., and others go as high as 650°, but a very common temperature is 550°. The oil quenching is done in a large tank or well, generally sunk in the ground, into which the steel is lowered immediately it is withdrawn from the furnace and allowed to remain until practically cold. It is then withdrawn and reheated. The oil tank is sometimes surrounded with a water jacket to cool it down as rapidly as possible. Brinell and Wahlberg's best results, or at all events results as good as any, both in tensile and impact experiments, seem to have been obtained by quenching from 850° C. and reheating to 550°, and owing to the smallness of the bars and consequent rapid cooling this would probably be equivalent to quenching from about 800° C. in the case of large masses of steel.

The following are some results obtained by Bunt† with oil tempered mild steel forgings made in the ordinary course of manufacture. The forgings were made from acid Siemens ingots, weighing about 15 tons each, which were forged down in a hydraulic press to square bars of approximately

* *Metallurgy of Steel*, p. 25.

† *Engineering*, June 13, 1902, p. 794.

one-fourth of the sectional area of the ingot. They were then rough-bored and turned, heated to a temperature of 700° to 800° C., plunged in oil, and, when cold, returned to the furnace and annealed at a temperature of about 500° C.

The test pieces, which were of the British Government standard size, were sawn from the full sized ends of the forgings—which were left a little long for that purpose—and, when possible, they were cut across the fibre.

TABLE CVII.—Ten Steel Forgings, Poor Quality.

Tensile Strength in Tons per Square Inch and Elongation per cent. on 2 Inches.

No.	Untempered.			Oil Tempered and Annealed.		
	Tons.	Elongation.	Fracture.	Tons.	Elongation.	Fracture.
1, . . .	29·56	21·09	Fair granular	39·31	26·43	Good.
2, . . .	32·57	23·44	Good.	35·75	24·21	Very good.
3, . . .	29·00	23·44	Bad.	35·39	24·21	Good.
4, . . .	31·78	21·09	Good.	38·34	23·43	,,
5, . . .	31·98	23·43	Fair.	39·91	24·21	,,
6, . . .	32·16	21·09	,,	37·89	26·56	Very good.
7, . . .	31·53	19·53	Bad.	41·04	20·31	Good.
8, . . .	28·93	23·43	,,	39·50	25·78	Very good.
9, . . .	31·50	19·53	,,	37·80	23·43	Fair.
10, . . .	31·50	20·70	,,	38·80	23·84	Very good.
Averages, .	31·05	21·67		38·37	23·93	

TABLE CVIII.—Ten Steel Forgings, Best Quality.

Tensile Strength in Tons per Square Inch and Elongation per cent. on 2 Inches.

No.	Untempered.			Oil Tempered and Annealed.		
	Tons.	Elongation.	Fracture.	Tons.	Elongation.	Fracture.
11, . . .	29·98	29·18	Good	37·80	27·34	Very good.
12, . . .	29·86	31·25	,,	39·58	23·43	Fair to good.
13, . . .	29·71	31·25	Very good.	39·51	22·65	Good.
14, . . .	28·55	30·46	Fair.	39·92	22·26	,,
15, . . .	29·61	28·90	Fair to good.	41·65	22·65	,,
16, . . .	28·55	30·46	Fair.	39·92	22·26	,,
17, . . .	29·73	32·81	Good.	37·71	25·78	,,
18, . . .	28·65	28·90	Fair.	39·32	25·78	Very good.
19, . . .	29·75	33·59	Very good.	41·74	22·65	Good.
20, . . .	28·84	31·25	,,	37·69	27·34	Very good.
Averages, .	29·32	30 80		39·48	24·16	

The average tensile strength and elongation of 200 forgings were as follows:—

Untempered: 32·01 tons per sq. in. with 27·34 per cent. elongation in 2 ins.

Tempered and annealed: 39·91 tons per sq. in. with 23·24 per cent. elongation in 2 ins.

This gives an increase in the tensile strength by oil tempering of 7·9 tons per square inch, or over 24 per cent. There is a decrease in the elongation, but

it is still good. The bending tests were satisfactory, and the fractures were fine grained. The results given in Table cvii. were selected from the worst of the forgings, while those given in Table cviii. were selected from the best. Unfortunately the elastic limit was not taken for the above samples, but from a number of experiments made on similar steels it was found to be increased about 50 per cent., or from 14·5 tons to 22·5 tons per square inch.

The results, as given in Table cviii., show an average increase in the tensile strength when oil tempered of 10·16 tons per square inch, or about 35 per cent. The elongations are still good, and taken with the bending tests show that the steel is very ductile.

An important paper by Messrs. Stead and Arthur W. Richards has been read before the Iron and Steel Institute * " On the Restoration of Dangerously Crystalline Steel by Heat Treatment." They conducted a series of experiments on steels varying from ·05 to ·46 of Carbon by first rendering them crystalline and brittle by heating to a temperature of about 1,260° C., and afterwards restoring the mechanical properties by heating for about 40 minutes at a temperature between 850° and 900° C. The steel in the condition as rolled, after overheating, and after restoring, was tested for tensile stress; for impact by a falling weight, by Brinell's compression test; and by a vibration test, by subjecting the specimens to rapidly alternating stress in a machine similar to that employed by Wohler. In every case the mechanical tests applied showed that the material after restoration was quite equal to, and in most cases superior to, what it was in its normal state as it left the rolls.

The microscopic examination showed that the heating of the bars to 1,260° C. caused a great development in the size of the grain, and the reheating to 870° restored the original or a better structure. It is not claimed that steel which has been "burnt" or heated to the point of near fusion, when a separation of the crystals occur, can be restored by the above treatment, but only steels which have been rendered crystalline by continued heating at a high temperature such as is liable to occur in everyday practice, even when the greatest care is exercised.

The above experiments are of special importance, as, with one or two exceptions, they were not carried out on small samples, but either on finished rails or on 5-inch blooms, so that the mechanical tests were such as engineers rely upon in everyday practice.

That steel, containing different percentages of Carbon, which has been rendered dangerously brittle by overheating, can be restored to the *best possible condition by a simple reheating to 870° without forging down to a smaller size*, is a fact of the greatest importance both to engineers and metallurgists, and shows what great possibilities there are of improving the mechanical properties of steel by submitting it to suitable heat treatment.

From the above results it would appear that by subjecting large forgings to a *final* heat treatment suitable to the special class of steel, it is possible to remove any dangerous crystallisation caused by overheating, as well as the internal stresses caused by forging, and to so produce a material in the best possible condition to resist varied and suddenly applied stresses.

These experiments emphasise the great importance of carefully controlling and regulating the temperature of the reheating of large masses of steel by means of a pyrometer, and confirm the conclusions of other investigators that the best results generally are obtained by heating for a short time to a temperature between 800° and 900° C.

Pyrometers. — One of the difficulties connected with the careful regulation of the temperatures of annealing and other furnaces, was

* *Iron and Steel Inst. Journ.*, 1903, vol. ii., p. 119.

formerly the lack of a pyrometer which would record over any required time the variations in temperature, and so enable them to be controlled. Many forms of pyrometers have been introduced from time to time, but few have been suitable for taking the actual temperature of a piece of steel during heating, or have enabled the attendant to see how the temperature was varying by reference to a dial with scale of temperatures or some equally ready method. The Uehling pyrometer, which is now being used in various works, is more suitable for taking the temperature of a hot chamber than that of any particular steel casting or forging. The Callendar electric pyrometer, which is a modification of the original Siemens pyrometer, depends upon the alteration in the electric resistance which takes place in a Platinum wire with a change of temperature; it is a very reliable instrument, and may be used either with, or without, an automatic recorder. It consists of fine Platinum wire wound on a mica frame, and it is made by the Cambridge Scientific Instrument Company. It has a very wide range, and can be relied upon from very low temperatures up to 1,200° C., although it is better adapted for temperatures between 500° and 900° C. The Platinum resistance is encased in a tube, so that it can be conveniently inserted in the source of heat it is desired to determine, and, when connected with a Whipple Temperature Indicator, the temperature can be read off direct. This pyrometer can be used with the Callendar recorder if a permanent record of the variations in temperature is required, and a continuous record obtained without the use of photography. The pyrometers are standardised, and, in the event of a breakdown, a new one can be connected to the recorder without loss of time.

The pyrometer designed by M. Le Chatelier, depending upon the following facts, is the instrument which has been found generally the most suitable, as it can be easily manipulated and is extremely accurate. It is now being largely used in many works.

If, when two wires or strips of dissimilar metals are joined together at both ends, so as to make a complete circuit, one of these junctions be at a different temperature to the other, a difference of electric potential is set up at the junctions, and an electric current traverses the wires. Such a pair of wires is called a thermo-electric couple. If the wires are of uniform composition, the potential difference depends on the difference of temperature alone, and the strength of the current will vary directly as the difference of temperature. If a galvanometer be inserted in the circuit this current can be measured, and if the current corresponding to various differences of temperature be once ascertained, the apparatus can be used as a means of measuring temperature. The current obtained from a couple of iron and German silver is fairly strong, but it cannot be used for high temperatures For temperatures approaching a red heat and upwards, the usual couple consists of a wire of pure Platinum, joined at one end to a wire of Platinum alloyed with 10 per cent. of Rhodium or Iridium. In works practice the galvanometer is usually situated at some distance from the source of heat the temperature of which is to be measured, necessitating the use of long wires. On account of the cost, the Platinum and Platinum-Rhodium or Platinum-Iridium wires cannot be used over the whole length, and copper leading wires are generally used to connect the couple with the galvanometer. This means the presence in the circuit of two extra thermo-couples—one Copper-Platinum, and the other Copper-Platinum-Rhodium, and unless care be taken to keep both of these at the same temperature, they will give rise to currents which will interfere with the current from the Platinum couple.

This difficulty can be overcome by placing the two copper junctions in a water jacket, which can be kept at a fairly constant temperature, which is

registered by a thermometer, so that a correction can be made for this when noting the temperature to be measured. For ordinary work a wooden box, to protect the junction from radiated heat, and in which is enclosed a thermometer to register the temperature of the surrounding air is found sufficient.

To form the hot junction the ends of the Platinum and of the Rhodium-Platinum wires are either fused together in the Oxyhydrogen blowpipe, or are closely twisted round each other, and the two wires are then kept separate for the remainder of their length, by threading upon them small fireclay or porcelain tubes. Instead of using separate fireclay tubes for each wire, single tubes with two holes for the wires to pass through may be used, and are supplied for the purpose. By this means the wires are completely insulated from each other except at the junction, and all fear of their short circuiting by coming into contact is avoided.

If the porcelain tubes are in lengths of 2 or 3 inches it enables the couple to be bent so that it can be placed in any position. For most furnace purposes the entire couple may be enclosed in an iron or porcelain tube to protect it from the direct action of the flame. When it is required to take the temperature of molten metals, the ends of the hot junction must be protected by a porcelain tube or other suitable device.

Before the instrument can be used it has to be calibrated, and this is done by determining the deflections of the galvanometer needle or mirror for the known melting points of a number of bodies, by plotting the temperatures and deflections obtained as ordinates and abscissæ, and drawing a curve through the points of intersection. The deflection of the mirror is read in the usual way by the movement of a spot of light reflected from the galvanometer on to a millimetre scale. By this means, provided a reasonable number of observations are taken through the range of temperature required, the difference in temperature between the hot and the cold junctions may be read off from any given deflection. The calibrating operation may be conducted as follows:—The substance to be melted is placed in a small crucible, which in turn is placed in a larger pot, and the annular space between the crucibles packed with dry fireclay. The crucible is then placed in the furnace, and the metal or other substance melted. The couple, protected by a fireclay tube, is immersed in the liquid metal, and the whole allowed to cool slowly. When the solidifying point is reached, the spot of light instead of continuing to slowly move across the scale will remain stationary for some time, this arrest being due to the latent heat of fusion evolved on solidification. This is taken as the point corresponding to the melting point of the substance.* In this way a series of points is obtained, those most usually employed being:—

Boiling point of water, .	100° C.	Melting point of aluminium,	657° C.
Melting „ tin, . .	232° C.	„ „ silver, .	962° C.
„ „ lead, .	327° C.	„ „ gold, .	1,064° C.
Boiling „ sulphur, .	445° C.	„ „ copper, .	1,084° C.

Before starting the determination of the melting points it is necessary to determine the zero of the instrument by bringing the hot and cold junctions close together, so that they acquire the same temperature, and noting the reading on the scale when the spot remains at rest. Metals, &c., of the greatest purity must be selected for calibrating purposes. The melting or boiling points of the above materials on the curve will correspond to the known temperature *minus* the temperature of the cold junction. Thus assuming the deflections for boiling water after deducting the deflections for zero of the instrument were 15 mm., and that the cold junction temperature was 20° C., 15 mm. would register a temperature of 100° — 20° C. = 80° C.;

* Copper during fusion should be covered with a layer of charcoal, as otherwise the solidifying point will be 8° to 10° C. too low.

that is to say, the difference in temperature between the hot and the cold junctions would be 80° C., and correspond to 15 mm. deflections. In the same manner the other points would be determined, and by plotting these points as suggested and joining them up, a curve is obtained from which the temperature for any given deflection can be arrived at.

Sir William Roberts-Austen's well-known recording pyrometer is the Le Chatelier pyrometer to which is attached a revolving drum carrying a sensitive Bromide paper, or a rising and falling dark slide, carrying a photographic plate moving at right angles to the beam of light, so that the light leaves a permanent record in form of a curve, showing the variations in temperature over any given period up to twenty-four hours. The pyrometer in this form is extremely valuable for practical purposes, as the registering galvanometer and recorder can be placed out of danger in the office of the manager or other convenient position, and any sudden variations in temperature due to carelessness or neglect on the part of the workmen, or from other causes, are at once shown on examining the curve.

A much cheaper and very convenient form of portable recording pyrometer of the Le Chatelier type is made by Messrs. Baird & Tatlock, and, although not so extremely accurate as the instrument designed by Sir William Roberts-Austen, it is sufficiently sensitive

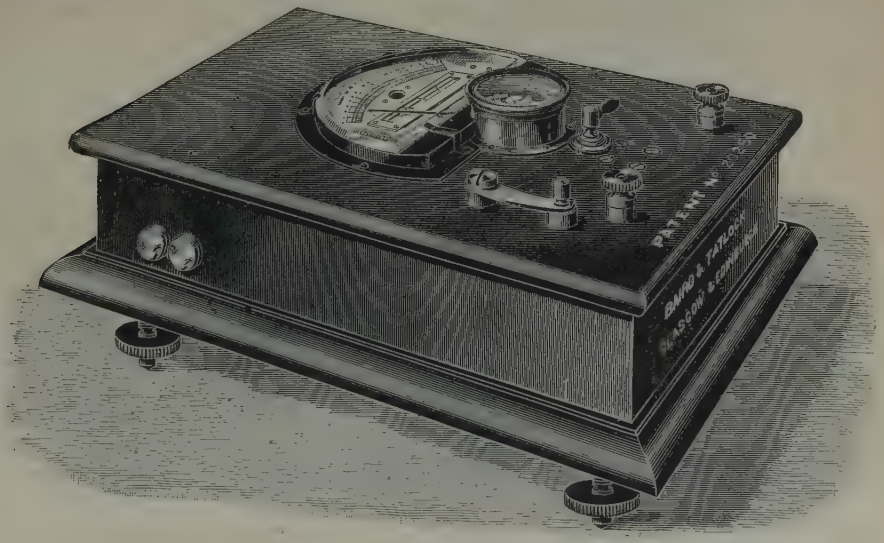


Fig. 260.

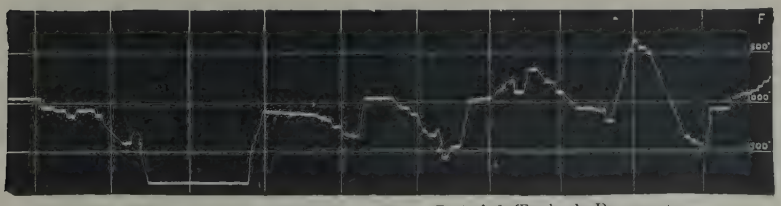


Fig. 261.—Photographic Curve from Baird & Tatlock Pyrometer.

for ordinary work. The galvanometer and recorder are contained in a small case about 20 inches long by 12 inches wide (fig. 260), and the whole can be carried about without affecting the calibration. The instrument is calibrated before being sent out, and the temperature can be read off direct from a scale attached, or, if desired, a permanent record for twenty-four hours can be obtained on sensitive paper. Fig. 261 shows a curve obtained in practice. Fig. 262 shows the iron tube containing the thermo-couple ready for inserting in the furnace, the cold junctions being protected from radiant heat by enclosure in a small wooden box as shown, with a thermometer attached for registering the temperature. In this sketch the tube is shown connected to a smaller form of registering instrument which is not provided with a photographic recorder. The wires forming the couple in the iron tube are insulated from each other by being drawn through small porcelain tubes. The insulated wires running from the cold junction are copper, and may be connected to the recording instrument any reasonable distance away, as in

Fig. 262.—Iron Tube containing Platinum-Rhodium thermo-couple. Junction ready for use. Wooden box attached contains the cold thermo-couple. On the left of sketch the box is open, showing method of making connections.

the office or elsewhere. If a number of furnaces at different distances are connected up to one instrument, a compensating switch is introduced into the circuit to allow for variations caused by the different lengths of wire connecting the furnaces.

Various modifications of this form of instrument are now made by different makers, and a very ingenious recorder, known as the Thread recorder, which gives a permanent ink record on a revolving drum, is made by the Cambridge Scientific Instrument Company for use with this class of pyrometer.

In steel works, pyrometers are used for controlling the temperatures of furnaces, ovens, baths, flues, &c., and also for the thermal examination of the metal as a guide for practical heat treatment. For controlling furnace temperatures, &c., almost any form of indicating arrangement may be

used either direct reading, scale reading, or some form of continuous recording instrument being employed, according to circumstances and exact nature of the work. For the thermal examination of steel, continuous recorders may be used or results may be obtained from simple lamp and scale readings using a mirror galvanometer, or the "differential" or "difference" method may be adopted.

This method consists essentially in eliminating the general cooling effect during the observation, and noting any differences in temperature of the metal under examination and another metal of similar thermal capacity, but having no critical changes in the range of temperature used during the experiment. For this second metal a piece of Nickel steel or Platinum is generally used. For these observations two galvanometers are required, one connected with a simple thermo-couple in the usual way to indicate the temperatures, the second galvanometer being connected with a compound couple, which only indicates any change of temperature in the two metals used. As these two metals are kept at the same temperature, the ray of

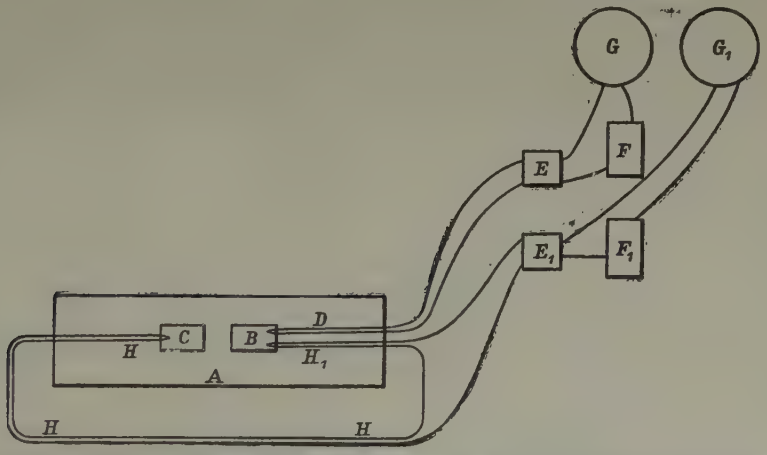


Fig. 263.—A, Electric furnace; B, steel under examination; C, neutral metal, Ni-steel, or Platinum; D, thermo-couple for temperature; E E_1, cold-junctions; F F_1, resistance boxes; G, galvanometer for temperature; H H_1, compound thermo-couple; G_1, differential galvanometer.

light from the second galvanometer will only move when heat is given out or absorbed by critical changes taking place in the metal under examination. Arrangements can be made in the photographic recorder to record the movements of the two galvanometers at the same time, or the readings may be obtained by lamp and scale arrangements.

In any case a curve can be obtained having as co-ordinates actual temperature and differences of temperature between the two metals—that is, heat given out or absorbed during the critical changes.

Fig. 263 is a diagram indicating the connections necessary for obtaining differential curves. A is a tube furnace containing an unglazed porcelain tube about 16 inches long and 1 inch in diameter, heated electrically by means of a coil of nickel wire or Platinum foil carrying about 20 amperes. B is a cylinder of the steel under examination; it is bored with two holes, one for the simple thermo-couple D, which is connected through the cold-junction E and resistance box F to the galvanometer G, which records the

temperature of the steel during heating or cooling. C is a cylinder of Nickel steel, having no critical points at the temperatures used, or a cylinder of Platinum bored with one hole and containing a thermo-couple H, one wire of which, say the Platinum, passes through the cold-junction E_1 and the resistance box F_1 to the differential galvanometer G_1, the other wire, say the Platinum-Iridium, passes to H_1, where it forms with another platinum wire a second thermo-couple, which is placed in the second hole in the steel under examination; this Platinum wire now passes through the cold-junction box E_1 to galvanometer G_1, thus completing the circuit. It will be seen that the thermal changes indicated by this galvanometer will be the algebraic sums of those of the metal B under examination and the neutral metal C.

Many workers prefer some form of potentiometric method to the simple galvanometric method of taking readings as being more accurate. Stansfield's * method consists of compensating the greater part of the E.M.F., leaving a small part to be read on the scale in the usual manner. A large cell is used to produce the balancing E.M.F., and a sensitive galvanometer used for reading. The sensitiveness may be so arranged that the scale, some 60 cm. long, represents only 10° to 15°. When the spot of light reaches the end of the scale, the resistance of the potentiometer is altered, so reducing the balancing E.M.F., and bringing the spot back to the beginning of the scale.

In both the Resistance and the Thermo-electric pyrometers the resistance coil or the thermo-couple has to be placed in the source of heat it is desired to measure, until it acquires the same temperature, and in many cases, especially in the case of molten metals of very high melting points, this is impossible. A great advance in pyrometry has been made by Professor M. Féry, of the École de Physique et Chimie, by his invention of a Radiation pyrometer, by which the temperature of any hot bodies may be determined by an instrument placed entirely outside the source of heat. The radiations which emanate from a hot body are made to fall upon a concave mirror, and are thus brought to a focus. In this focus is a thermo-electric couple whose temperature is raised by the radiations falling upon it; the greater the temperature of the body, the greater the amount of heat radiated, and the greater the rise in temperature of the couple.

The complete instrument consists of a telescope connected with a sensitive galvanometer: within the telescope, at a point upon its optical axis, is fixed the junction of a Copper-constantan thermo-couple, arranged in the form of a cross and connected by wires with terminals on the outside of the telescope (fig. 264). These terminals are connected by leads with a

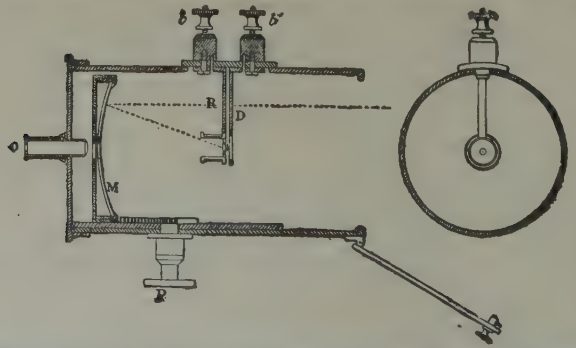


Fig. 264.—Féry Radiation Pyrometer Telescope—O, Eye-piece; D R, two brass strips attached to terminals, *b b'*; *b b'*, terminals for leads to galvanometer.

* *Phil. Mag*, 1898, vol. xlvi., p. 59.

galvanometer, which may be provided with a temperature scale; or, if a permanent record is required, the Thread recorder may be used.

To measure the temperature of a furnace, an observation hole must be provided and sighted through the eye-piece of the telescope, the image of this hole being brought into coincidence with the thermo-junction; the image of the hole is reflected to the eye-piece by two mirrors placed close to the thermo-couple. These mirrors serve for the adjustment of the focus, and are so arranged that the image of the hole appears to be split into two parts, which only coincide when the focussing is correct. It is essential that the image of the observation hole should slightly overlap the junction, which appears to the eye as a black disc in the centre of the field of view. The image formed upon the thermo-junction produces a rise in temperature, which has been shown experimentally to be proportional to the amount of radiant energy which enters the telescope; the junction rapidly acquires the exact temperature of the image, and the electro-motive force thus generated is measured by a very sensitive galvanometer.

In order that the amount of radiation falling upon the thermo-couple may be varied, an adjustable diaphragm is fitted in front of the telescope, and, when measuring very high temperatures, the diaphragm partially covers the aperture of the telescope (fig. 265, B) Within very wide limits, the readings obtained with the instrument are uninfluenced either by the size of the hot body or the distance of the hot body from the instrument; the amount of radiant heat absorbed in passing through the atmosphere is so small, and, in measuring temperatures of from 1,000° to 1,200° C., it has been found experimentally that, whether the hot body was 3 feet or 60 feet from the instrument, there was no appreciable difference in the readings. To avoid any possible error, however, it is recommended that the diameter of the furnace opening, or the hot body, should measure as many inches as the distance between the source of heat and the instrument measures yards. The pyrometer is more sensitive at high temperatures than low, owing to the fact that the energy radiated from a hot body increases very rapidly with the rise in temperature, but temperatures as low as 600° C. can be measured.

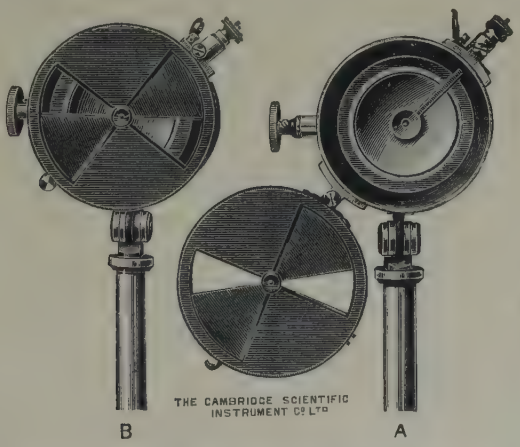


Fig. 265.—Féry Radiation Pyrometer, showing Diaphragm for Reducing Aperture of the Telescope.

The Uehling pyrometer before referred to is based upon a principle entirely different from those already described, and depends upon the flow

of air through small apertures under a constant suction. A tube has an aperture of the same size at each end—one end is placed in the source of heat, and the other end cooled to a constant temperature and connected with a chamber, in which a constant suction pressure is maintained by a steam jet. As air expands with heat, the higher the temperature to which the air entering the hot end of the tube is raised, the smaller will be the quantity of air drawn through the aperture by a given suction, and, as the air is considerably cooled to a constant temperature before it reaches the aperture at the other end of the tube, a greater quantity of air will be drawn out of this aperture than is drawn in through the opening at the hot end, so that the suction will increase in the tube and decrease in the exhaust chamber. The suction being kept constant by a specially-designed regulator, the velocity of the air passing in through the hot end of the tube will increase, and the velocity of the air passing out through the cold end will decrease, until the same quantity of air flows through both. Therefore, every change of temperature in the air entering at the hot end of the tube will cause a corresponding change in the pressure in the tube, and by connecting manometers with the tube and with the exhaust chamber, the constant pressure in the exhaust chamber, and the variable pressure in the tube, can be registered, and this latter is a true measure of the temperature of the hot air entering, and can be read off direct from a scale attached. The details of the instrument as supplied commercially have been worked out with the greatest care and ingenuity, but space does not permit of a description of these, as this could be given only with a series of diagrams. Full particulars can, however, be obtained from Messrs. J. Wild & Co., Middlesbrough. One great advantage of the pyrometer is that it has an automatic recorder, seven hours of which are always in view, so that all variations for this period can be seen at a glance. It is especially adapted for recording the temperature of hot gases, or of large heated chambers, such as annealing furnaces, and a large number are in use both in Europe and in America.

CHAPTER XIX.

MICROSCOPICAL EXAMINATION OF STEEL.

The study of the microstructure of steel originated with Dr. Sorby of Sheffield many years ago, but for a considerable time after the publication of his first paper little attention was given to this method of research in this country, although substantial progress was made in Germany by Professor Martens. It is only during the last fifteen years or so that British metallurgists have given the subject serious consideration, but during that time it has been extensively studied and progress has been very rapid, so that now the microscopic examination of iron and steel alloys is not only largely carried out in all laboratories devoted to scientific research, but has become an essential part of the work of many of the chemical laboratories connected with our leading steel works.

Microscopic examination not only aids in the determination of the soundness of a steel and the detection of mechanical defects, but also throws much light on its internal constitution and the heat treatment to which it has been subjected, and it is in the latter relation that the greatest assistance may be anticipated from the use of the microscope.

The term "microscopic metallography" has been assigned to the method of microscopical examination of metals in general.

Preparation of Samples.—In order to examine the structure of metals microscopically it is necessary first of all to polish a small section until it is as free as possible from even the most minute scratches.

The details of the methods employed vary with different investigators, but in general principles they are alike, and consist of first filing the sample as dead true as possible, then grinding on an emery wheel, and polishing, either by hand or on revolving wheels covered with emery paper of different degrees of fineness, and finally buffing up on a cloth, kidskin, or similar disc with some fine polishing powder. The details of the methods used by Sorby, Osmond, Roberts-Austen, Arnold, Martens, Stead, Ewing and Rosenhain, Le Chatelier, and Sauveur respectively are given below, and it is most desirable that the student should try the different methods, and adopt the one which he finds gives the best results for the particular material with which he has to deal.

Sorby's Method.—Dr. Sorby used small slices, about $\frac{1}{10}$ of an inch (2·5 mm.) in thickness, and by filing, and grinding on an emery wheel obtained as true a surface as possible. The section was then fixed on a glass plate with a little Canada balsam and the surface further ground by rubbing backwards and forwards on, first coarse, and afterwards finer grades of emery paper fixed on a glass support. Before polishing, the surface of the sample was ground on fine-grained Water-of-Ayr stone, which removes all the scratches left by the emery. The final polishing was then effected by rubbing the sample with some crocus powder and afterwards with the finest levigated rouge on a wet cloth stretched over a flat piece of wood, which was kept moist by adding a few drops of water occasionally during the time of rubbing.

It sometimes happens that the sample contains some portions softer than others, and this method causes the surface to be worn away unequally. In

cases where it was desirable to have all the constituents of the polished surface on precisely the same level and the specimen not rounded at the edges, Dr. Sorby performed the final polishing with dry rouge on a sheet of parchment stretched over a glass plate; some of Dr. Sorby's most beautiful specimens were polished dry and not etched by acid, &c. By the dry method some of the constituents are left quite bright and metallic, whilst others assume a blue appearance.

Osmond's Method.—Osmond pointed out that it is very important that the sample should be cut cold and not in any way distorted. He followed very closely the original method of Sorby, but used a machine for the final polishing, and did not fix the specimens to a support, but simply held them between his fingers. In the final polishing he used a method of "Polish attack," which consisted in rubbing the sample on a sheet of parchment covered with precipitated Calcium Sulphate moistened with an infusion of liquorice, by which means some constituents of the steel were coloured. The liquorice infusion, however, does not keep very long, and attacks the sample unequally when a day or two old. In the *Metallographist* for January, 1900, Osmond recommended the use of a 2 per cent. solution of Ammonium Nitrate as far preferable to the liquorice solution. When he required a polished unetched surface he finished either on cloth or kidskin with some fine polishing powder.

Roberts-Austen's Method.—The method used by the late Sir Wm. Roberts-Austen is almost identical with Osmond's, each sample, after filing and grinding, being polished on emery paper of different grades fixed on wooden discs which are revolved at very high speeds by a motor. The final polishing may be completed either by the "Polish attack" of Osmond, or by a disc covered with cloth or kidskin, and by using the finest rouge or similar powder.

Arnold's Method.—The following are the details of the method employed by Prof. Arnold as communicated to Mr. Stead*:—

The sections employed are $\frac{1}{2}$ inch in diameter and $\frac{1}{10}$ inch thick. Before leaving the machine shop they are finished with a dead smooth file, and the file marks are removed by rubbing on a piece of the finest emery cloth, lightly stretched on a hard-wood board. The remaining operations are carried out on materials stretched by means of rings on machined circular tapered cast-iron blocks.

On No. 1 block is the finest emery cloth from which the coarser grains have been removed by rubbing, first with a marble slab, and secondly, with a piece of smooth hard steel about 1 inch diameter by $\frac{1}{4}$ inch thick. On No. 2 block is stretched thick black unribbed cloth, charged with oil and the finest emery knife polish. On No. 3 block is a piece of the finest wash leather slightly charged, dry, with the best jeweller's rouge. The average times occupied in each stage are as follows:—On emery cloth five minutes, and on Nos. 1, 2, and 3 blocks about ten minutes each. The plan of rubbing off the coarser grains of emery from the commercial papers Mr. Stead finds is excellent, and does away with the necessity of personally preparing fine emery papers, and the author's experience fully confirms this.

Martens' Method.—In the case of steel, the samples are cut about 2 to 5 mm. thick with a saw or file, but for brittle iron and spiegeleisen it is necessary to chip a piece off with a chisel, and then grind it flat on a grindstone or emery wheel. Martens often polishes a large number of specimens at the same time by cementing them in a circle on a plate of glass. For this purpose he uses a cement made by melting together equal parts of beeswax and resin.

* *Iron and Steel Inst. Journ.*, 1894, vol. i., p. 396.

The plate to which the specimens are attached is then put in a lathe, and the surfaces of the samples are turned until all are of exactly the same level.

In the case of very hard or brittle samples the levelling must be done by grinding.

For the preliminary polishing he uses emery (Corundum), pounded quartz, sand, and oilstone, and for the fine polishing, hard, and soft, polishing rouge. All his grinding and polishing powders are very carefully levigated before use; in fact, he gives this as a *sine qua non* for successful work, and recommends that each operator should prepare his own powders.

For grinding beds he uses plates of glass, cast iron, copper and lead, and for polishing beds plates of glass or pitch, and sometimes soft beds, such as india-rubber, leather, or cloth. The beds are selected according to the hardness of the material to be polished. He states that the pitch beds are best prepared by melting soft pitch, with the addition of a small quantity of resin, and pouring the mixture on to plates of glass. He finds that the time necessary for preparation by this method varies with circumstances and the experience of the operator, at first several days may be necessary to obtain a single polished surface, but, after a little practice, what formerly took weeks to do may be accomplished in a few hours.

Stead's Method.—Stead prefers to have the sections cut about $\frac{3}{8}$ or $\frac{1}{2}$ inch in diameter and about $\frac{1}{10}$ inch thick, and filed as smooth as possible with a dead smooth file. The section is then rubbed on emery paper of the grade known as No. 0 English, and then successively on Nos. 0, 00, and 000 French paper until all but the very finest scratches are removed. Polishing is then finished on wet cloth with diamantine powder, and finally on chamois leather with fine washed jeweller's rouge. This treatment gives results which are quite sufficient for all ordinary work, but for the very finest work under high powers the final polishing is done on wet parchment or kid skin with rouge. Stead * has designed a machine for polishing micro sections, sketches of which are given (figs. 266 and 267). At first he did the whole of his polishing on this machine, but latterly the rubbing on the first three grades of emery paper has been effected by hand, using the paper stretched or glued to blocks of wood about 5 inches square. The smoothest grade of paper and the cloth and chamois leather he still uses on the machine.

Stead usually requires from 10 to 15 minutes for an average sample of the sizes given above.

More recently Stead has designed another machine which can be driven either by hand or power, in which the specimens are held in movable clips over the polishing bed, and can be transferred in the clips to the microscope stand for examination, and, if any further polishing is necessary, can be again placed on the polishing machine. As the specimen is not removed from the clips during examination it can be refixed in the polishing machine without altering the relative position of the surfaces of the specimen and the polishing disc, and so ensures the polishing being continued in the same plane.

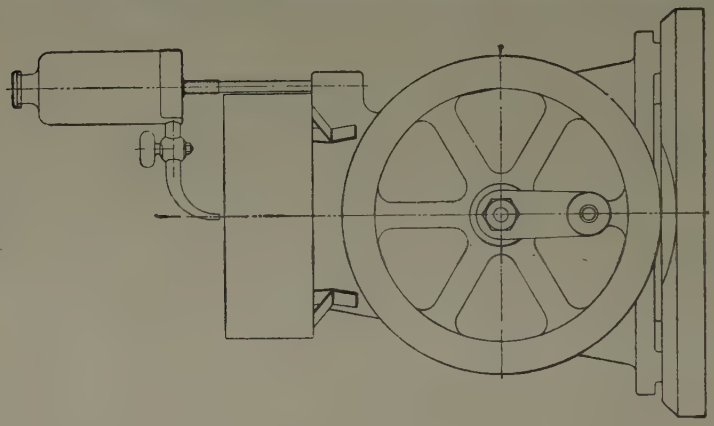
Ewing and Rosenhain's Methods.†—These operators rub the specimen on various grades of commercial emery paper from which the coarse particles have previously been removed by rubbing with a piece of flat steel as suggested by Arnold. The specimens are then finished on a rapidly revolving disc, covered with fine wash leather, charged with a thin paste of rouge and water. The rouge used for the finest work is specially prepared by precipitation from a solution of pure Ferric Chloride. In the

* *Iron and Steel Inst. Journ.*, 1894, vol. i., p. 305.
† *Phil. Trans. Roy. Soc., London*, vol. cxciii., p. 353.

case of samples easily tarnished wet polishing is avoided, and either the rouge is used dry or it is moistened with paraffin on the wash leather.

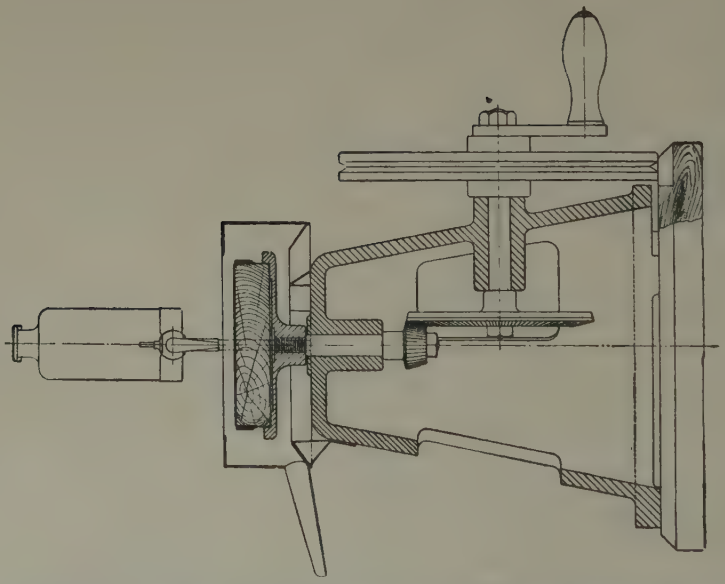
Mons. H. Le Chatelier has made some very important investigations on the best methods of preparing the polishing powders, as upon this, he considers, largely depends the success of the subsequent polishing opera-

Fig. 267.



STEAD'S POLISHING APPARATUS.

Fig. 266.



tions, and also the length of time occupied. He also adapted Schloesing's method for the analysis of Kaolin to the washing and classification of the various materials used. The following description of the method is taken from Le Chatelier's paper in the *Metallographist** :—

"Mr. Schloesing treats the powders which he desires to classify with water containing 1 part of Nitric Acid in 1,000 parts of water, in order to

* *Metallographist*, vol. iv., No. 1.

dissolve the Carbonate and Sulphate of Lime and other salts which might be present. After standing a few hours, with occasional stirring, the mixture is allowed to settle. The powder falls rapidly to the bottom, and the clear liquid above it can be easily decanted. This liquid is now replaced by distilled water, and the mixture stirred; it is then again allowed to settle, and decanted. After a few similar operations, when all the acid has been removed, the settling takes place more slowly, and the liquid remains milky. The conditions are now favourable to proceed with the levigation, and the operation is further facilitated by adding 2 cubic centimetres of Ammonia to each litre of water, as it helps the suspension of the finest particles. Decantation is now resorted to, at stated intervals, by means of a syphon having a hook at its extremity, so as to avoid disturbing the portions which have settled.

"By treating 10 grains of powder in a 1-litre flask, nine-tenths of the liquid may be syphoned off without fear of disturbing the deposit.

"The decantations are made at the following intervals—fifteen minutes, one hour, four hours, twenty-four hours, and eight days.

"The deposit left after the first decantation contains all the coarse grains unsuitable for polishing. The second deposit, resulting from the first decantation, after one hour's settling, yields a substance which is not yet very homogeneous, but which may serve to start the polishing. The third deposit constitutes a good polishing powder for hard metals. It is, however, the deposit collected between the first and eighth day which constitutes true polishing powder. Instead of waiting eight days for the formation of the last deposit, it may be precipitated immediately after the removal of the 'twenty-four hours' powder by adding some Acetic Acid to saturate the Ammonia. The powder, still remaining in suspension, is then deposited after a few hours. The only objection is that some very fine particles, which would have remained suspended after eight days, are also precipitated.

"Once prepared, the powders must be carefully kept and contamination by any foreign matter avoided.

"A method which has given me very good results consists in converting them into a paste by mixing with soap. To do this, a piece of very dry Castile soap should be shaved by means of a very clean knife. The flakes of soap thus obtained are added to the polishing powder, when the latter is still wet, in the proportion of 1 part of dry soap to 10 parts of the wet powder. The mixture is melted in a water-bath, and allowed to cool, stirring all the while, until the mass begins to thicken; it is then poured into tin tubes similar to those used for keeping oil paint. After complete cooling the tubes are closed, and in this way the paste can be preserved very conveniently."

Le Chatelier has found that the substances which give the most satisfactory results are: commercial flour of emery; Oxide of Chromium (prepared by igniting Ammonium Bichromate); Alumina (obtained by the calcination of Ammonium Alum); and Oxide of Iron (from the strong ignition of Oxalate of Iron in the air). Alumina is considered to be very much superior to the others, both as regards results obtained and the expenditure of time.

Le Chatelier recommends, as supports for these powders, albumen, leather, cloth, velvet, and felt.

The method followed by him in polishing his samples is—first, to rub on commercial emery papers of various grades until all but the finest scratches are removed. This part of the polishing is done by hand. For the final polishing he uses first a disc covered with an emery paper, prepared with albumen and the washed powder which settles out after the second decan-

tation. Next, a felt or cloth disc upon which is placed some soap paste made with Alumina, which settles out between one and four hours; and finally, a disc of wood or ebonite to which is glued cloth or velvet covered with soap paste made from the Alumina deposited after twenty-four hours. The last three discs are rotated at as great a speed as possible, and for this purpose he uses a small machine made by Mons. Grauer, of Paris, worked by means of a treadle, and having the discs in a vertical position thus avoiding grit and dust settling on them. The discs have to be kept constantly moistened, and the sample is rotated in an opposite direction to that of the disc in order to avoid the rounding of the edges and the tearing open any small cavities or pits which may exist in the sample. M. Le Chatelier gives about five minutes as the time of polishing. He uses various reagents for etching, and recommends, amongst others, absolute alcohol containing 10 per cent. of gaseous Hydrochloric Acid to which from 1 to 5 per cent. of Anhydrous Copper Chloride has been added.

Sauveur's Method.*—Sauveur practically follows the method of Le Chatelier, except that he uses a paste made of tripoli and Castile soap for polishing. For general work he considers the treatment with rouge may be omitted, and altogether the entire polishing operation may consist of only three treatments. The machine is one of his own design, and carries four discs, which revolve in a vertical plane. Water is fed on near the centre, the rapid revolution of the discs causing it to be distributed over the whole surface. The machine is driven by a motor, and one operator can polish two samples at the same time. For a sample $\frac{1}{4}$ inch square, five or six minutes is sufficient for the whole operation.

The author uses a combination of several of the above methods. After sawing cold, the specimen, which is usually about $\frac{3}{8}$ to $\frac{1}{2}$ inch square and of suitable thickness, is filed as smooth as possible, and is then rubbed by hand on three grades of emery paper fixed to wooden blocks. For general work it is then only necessary to give one further treatment, which is effected with Alumina soap paste on a revolving cloth disc driven by a motor. For finer work rouged kidskin is used, when as fine a polish as can be desired is obtained in ten to fifteen minutes, according to the size and nature of the sample. In many cases excellent results have been obtained by Osmond's "Polish attack."

Development of Structure.—In the great majority of cases before the sample is examined under the microscope it is advisable, and generally necessary, to etch the polished surface to develop the structure, and various reagents have been suggested for this purpose.

Nitric Acid Etching.—Sorby used dilute nitric acid, and for ordinary work this gives good results, the strength of the acid being varied to suit the requirements of the case. Sir William Roberts-Austen for most work used a 1 per cent. nitric acid solution in alcohol; Osmond used a solution of 20 and 2 per cent. respectively of 1·33 specific gravity acid; Arnold recommends 1 part of nitric acid of 1·2 specific gravity in 49 parts of water, or 1 part acid in 199 parts of water, and for some purposes a still more dilute solution. Sauveur etches by immersing the specimen in nitric acid of 1·42 specific gravity for a few seconds, when the iron assumes the passive state. It is then well washed under a good stream of water, when a very slightly and evenly etched surface is obtained, free from the deposit of Carbon which is formed when dilute acids are used. By repeating the process any desired depth of etching may be obtained. Campion † also

* *Metallographist*, vol. iv., No. 4.

† *West Scot. Iron and Steel Inst. Journ.*, vol. vii., No. 2, 1899.

strongly recommends this method of etching, and the author has also found it to give excellent results. When nitric acid, either dilute or strong, is used the specimen, after well washing in water, should be rinsed in alcohol and afterwards wiped with a soft cloth moistened with benzene. It is then ready for examination under the microscope.

Iodine Etching.—Osmond recommends, for general work, tincture of iodine of B.P. strength, and prefers this to nitric acid, while Le Chatelier also prefers this reagent. The latter places some of the iodine solution on the polished surface, and gently rubs the surface with the finger-tip in order to obtain uniform etching and to prevent the constituents in the steel unacted upon from becoming tarnished. Stead prefers, for general work, tincture of iodine made by adding 1·25 grams of iodine and 1·25 grams of potassium iodide to 1·25 c.c. water, then adding alcohol to make the total volume 100 c.c. Sometimes he uses a tincture of one-fourth the above strength. He applies the iodine by placing 1 drop per sq. centimetre on the polished surface and leaving it until the liquid is decolorised, when the specimen is washed in water and alcohol and dried in a current of hot air. This treatment can be repeated until the structure is developed to the required extent. Ridsdale, for the determination of the size and definition of grain, uses a half-saturated solution of iodine in alcohol, immersing the specimen for one or two minutes and afterwards washing in water and methylated spirit or alcohol. The specimen is dried by heat or is lightly rubbed with chamois leather.

Etching with Picric Acid.—This reagent was suggested by Igevsky,* who uses a 5 per cent. solution in alcohol. It gives most excellent results, one of the chief advantages being that the Ferrite is not attacked or coloured, and the mottled appearance so frequently noticed after etching with nitric acid is avoided; it develops the structure with great clearness both in hard and annealed steels, is probably one of the best reagents yet suggested, and is very largely used.

Other Methods of Etching.—The "Polish attack" of Osmond with precipitated sulphate of calcium and liquorice infusion or 2 per cent. solution of ammonium nitrate on parchment is really a combined polishing, staining, and etching process. Martens also uses an alcohol-ether solution of hydrochloric acid. He has also shown that, by heating, the different constituents in the steel assume various colours, by which they may be distinguished under the microscope. Stead has used this method of heat tinting with much success for the examination of phosphoric steels, and has stated that this is the only way at present in which Phosphides and Carbides can be distinguished from one another when present in steel. The following directions for heat tinting are taken from Stead's paper, "Practical Metallography," read before the Cleveland Institution of Engineers in February, 1900:—

"In preparing the specimen for heat tinting, the bright surface should be well rubbed with a clean piece of linen or chamois leather; care must be taken to avoid any condensation of water on the surface; this is best secured by warming the specimen to 90° or 100° C. before giving it a final vigorous rubbing with the linen or chamois leather, and before it cools it should be placed on the iron plate. A sheet of iron, 6 inches square, placed over a Bunsen burner is all that is required for heat tinting. The section is placed in the centre, and the polished surface watched until the proper tint is obtained. Practical experience will soon enable one to find the best tint for any particular metal or alloy. It is advisable to heat gradually and examine periodically under the microscope, and stop when the structure appears to be most perfectly coloured. After each heating

* *Stahl und Eisen*, 1903, vol. xxiii., p. 120.

the section should be placed in a dish containing Mercury, so as to cool it rapidly and check further oxidation. If it is desired to photograph the heat-tinted object, it is most important in many cases to stop the heating when the object assumes a pale yellow tint, for although the contrasts to the eye are not so great, they are quite great enough for the sensitive photographic plate."

Saniter * has proposed a method of hot etching with fused chloride of calcium in order to develop the structure of steel at high temperatures. The calcium chloride is melted in a platinum crucible and heated to the desired temperature. The sample to be etched is placed in the fused mass and allowed to attain the same temperature. When this has occurred the whole is rapidly cooled by plunging the lower part of the crucible into cold water, &c. The adhering chloride is then dissolved off.

Various other etching media have been suggested from time to time, such as chromic acid mixture, sulphuric acid, potash, potassium sulphate, &c., but those described above are the ones most generally used. The best method to adopt for developing the structure depends entirely upon the nature of the material under examination, the previous treatment to which it has been subjected, and the particular structure it is desired to examine. In some cases it may be necessary to compare the structure of the same section which can be developed by different methods. Probably picric acid or the combined polishing and staining method of Osmond is the best to use for developing the structure of the various microscopic constituents under very high powers, especially in the case of annealed steels. For the development of structure, and in cases where measurement of size of grain is required, 1 per cent. of nitric acid in alcohol, tincture of iodine, and strong nitric acid, with subsequent washing, all give very good results. Considerable experience is required in order to know which reagent will give the best result in particular cases, and nothing but repeated examination of various samples, etched by different methods, will enable the student to decide which is the best to use in any particular case.

Microscopic Apparatus.—Space will not permit of a detailed description of the microscope, and for this the student must be referred to a standard treatise on the subject, but there are several points in connection with the microscope to which it is desirable to call attention, and some special accessories used in examining metallic sections which it will be necessary to describe. Any good microscope stand may be used—preferably arranged to be used in a horizontal position—and it should have a sensitive fine adjustment. The base should be sufficiently large and weighty to render the instrument perfectly steady for the use of high power objectives. Metallic objects, being opaque, cannot be examined by transmitted light, and consequently special illuminating apparatus has to be used even for moderately high powers.

Illuminating Apparatus.—The illumination used may be either vertical or oblique, and in many cases it is desirable to examine the specimen by both. For low power objectives the light may be thrown on to the object by means of reflectors placed *below* the object glass, but for high powers they must be placed *above*, that is between the object glass and the eye-piece of the microscope. For examination with low powers the Sorby-Beck reflector i the most useful type of illuminator, and by its use either vertical or oblique illumination can be obtained.

The construction of this illuminator is shown in fig. 268. It consists of a parabolic reflector to which is attached a little silver mirror, with a face at an angle of 45°, which can be turned away from or under the object glass by means of the milled head, A. When oblique illumination is required,

* *Iron and Steel Inst. Journ.*, 1897, vol. ii., p. 123.

the mirror is thrown outside into position shown by the dotted lines (fig. 268), and the specimen is examined by light reflected from the silvered parabola, S. When direct illumination is desired the little mirror is turned back into position shown in fig. 269, so that it partly eclipses the object glass, but leaves room for the horizontal rays, L, reflected from the mirror on to the object to be reflected back from its surface into the microscope.

In the case of oblique illumination the horizontal rays of light, L (fig. 270), falling on the parabola are reflected at various angles up n the object below, and if the surface is perfectly flat none of this light is reflected back into the microscope, and consequently such a surface appears quite black, and cannot be seen with the microscope. If, however, one constituent is in relief as the light falls upon one side of the projecting portion, the light is reflected back into the microscope, and it appears brilliantly illuminated, leaving the other side in shade. Oblique illumination is therefore very useful for determining which constituent is in relief, and which part of a structure is broken up.

When direct illumination is required for low powers, instead of using the Sorby mirror, a very simple arrangement suggested by Stead* will be found to give excellent results. The device is shown in fig. 271. A piece of blackened cardboard is fixed behind the object in a vertical position, and a cover-glass, *g*,

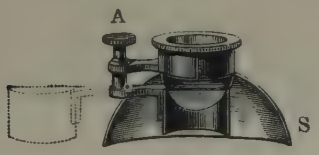


Fig. 268.—The Sorby-Beck Reflector.

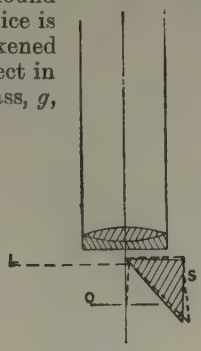


Fig. 269.

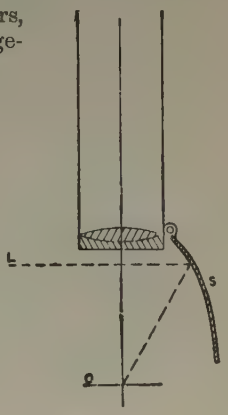


Fig. 270.

is placed over the object at an angle of 45°, both being temporarily attached to the slip holding the object with plastic wax. The horizontal rays of light are reflected down by the cover-glass on to the object, and then back from the object through the cover-glass into the microscope, as shown in the sketch.

For high powers above $\frac{2}{3}$ of an inch, direct illumination is always used, and Beck's illuminator is a very useful form. It is exactly similar in principle to that last described except that the reflector, which is a cover-glass, is above the object glass, as shown in fig. 273. It consists of a metal collar or tube in which is fixed on a pivot a cover-glass which acts as a reflector, and which can be rotated to any angle by the milled head shown, light being admitted to the reflector through an opening, A, in the metal tube (fig. 272). The collar is screwed into the microscope tube, and the objective then screwed on to the bottom of the collar, so that the reflector is in the tube of the microscope. The reflector is turned to an angle of 45°, rays of light, L, admitted through the opening, *a*, fall upon the reflector, G (fig. 273), are reflected down on to the object, and then up from its surface through the object glass and reflector to the eyepiece. The above illustrations are from blocks kindly lent me by my friend Mr. Stead, who had them specially prepared to illustrate his paper on "Practical Metallography." Professor Martens and others use

* "Practical Metallography," *Proceed. Cleveland Inst. of Engineers*, Feb. 26, 1900.

a right angled prism fixed in the microscope tube in the same manner as the cover-glass in the Beck reflector.

Fig. 275, for which I am indebted to Mr. Carl Zeiss, shows this form of illuminator, and the sketch in fig. 274 explains how the light is reflected.

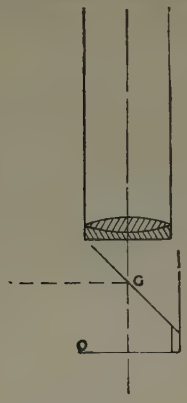


Fig. 271.

Beck's Illuminator.

Fig. 272.—Reflector.

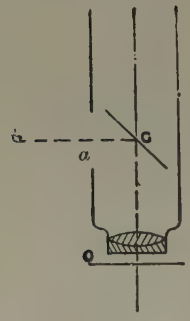


Fig. 273.

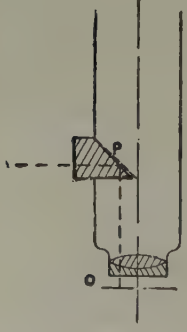


Fig. 274.

Fig. 275.

Light for Illumination.—For ocular examination any ordinary oil lamp may be used with good results up to about 150 diameters. A Welsbach gas burner or acetylene lamp is, however, preferable, and may also be used for photographing up to about 250 diameters, but for very high magnifications the electric arc is necessary for good and rapid work. Between the source of light and the illuminator a bull's-eye condenser should be placed to concentrate the rays. There are many forms of cameras to be obtained for photomicrography, and they may be made to work in either a horizontal or vertical position. The camera with which all the photographs that follow were taken was a horizontal one similar to that shown in fig. 276.

In taking a photograph the object should be first carefully focussed under the microscope in the usual way, and without removing the eyepiece, the hood of the camera pushed over the latter, and the camera extended to give the magnification required. The final focussing is best done on a plain glass plate instead of the usual ground glass camera screen, and, a No. 1 eyepiece being placed on the centre of the glass, the fine adjustment micrometer screw is turned until a very distinct image of the object is seen. If the illumination is good the focussing can be done directly on the ground glass screen without an eyepiece and excellent results obtained. The glass screen is then replaced by a slide with a photographic dry plate in position, the slide drawn and an exposure made. The time of exposure will depend upon the magnification required, the source of illumination, the rapidity of the plate, and to some extent upon the object, and it is a matter of experiment to determine what length of exposure gives the best results for the particular conditions. Using an arc lamp and plates

of medium speed, the author finds from six to ten seconds exposure sufficient for magnifications of 100 diameters, and for 1,000 the exposure will vary from 20 to 30 seconds. The photographic plate may be developed in the usual way.

When purchasing a microscopic outfit it is far cheaper in the end to go to one of the first-class makers, and the following list of microscopic accessories may be considered necessary for good all-round work, although a beginning can be made with less :—

Fig. 276.

Microscopic Accessories.

1 microscope stand of any reliable maker.
Objectives.—1 planar objective 35 mm.
2 projecting aplanats 35 mm. and 70 mm.
1 apochromatic 16 mm.
1 oil immersion 3 mm.
Eyepieces.—Huyghenian, No. 2, for general examination.
Projection, Nos. 2 and 4, for photography.
Some suitable source of illumination.
1 Beck reflector for low powers.
1 Zeiss or Nachet prism reflector.
1 micrometer slide (1 mm. divided into 1,000 parts).
1 camera specially designed for micro work, and if of considerable length an arrangement for working the fine adjustment from a distance, such as "Hook's Key," must be fitted.

Microscopic Examination.—The microscopic examination of steel samples may be considered under three heads :—(1) General examination for mechanical defects ; (2) examination for size of grain and general crystalline structure ; (3) examination to determine the microstructure and to identify the micro-constituents present and their distribution through the steel.

Examination for Mechanical Defects.—In this examination the surfaces to be examined must *not* be ground down, as this would remove small cracks or flaws. The best way is to rub with very fine emery paper (No. 000) afterwards on paper No. 0000, and finally on rouged chamois leather or kidskin. A somewhat pitted surface will be left, suitable for examination under a low power. If nothing is visible the specimen should be immersed in a 1 per cent. solution of nitric acid for a few seconds, and well washed, first with water, then limewater, and then water again. After rubbing with the rouged chamois leather, it should be again examined. If nothing is visible, repeat the treatment; if still no cracks or defects are visible, treat again, this time using 10 per cent. acid for about a minute. If nothing now appears, surface cracks and flaws may be considered absent. The above treatment is very useful when examining the running heads and surfaces of rails and tires, &c. This examination is always made with a very low power.

A method which very often gives valuable results for rails, tires, axles, and similar sections is to cut a complete cross-section of the article to be examined, and, after covering one face and the edges with wax or acid-proof varnish, to immerse it in a 20 per cent. solution of sulphuric acid kept at a temperature of 60° C. for a quarter of an hour, and then well wash in water. Slag flaws, blowholes, rolling cracks, &c., are generally made clearly visible. In some cases half an hour's action of the acid may be necessary.

Steels containing a large amount of Sulphur or Phosphorus often show deep, uneven pits and seams after treatment in this way, and the information obtained is frequently of great assistance in determining where to cut the sections for the subsequent microscopic examination.

Samples of wire rod which have failed, very frequently exhibit a central crack or hollow cavity when treated by this method, especially such samples as break with what is known as a "cuppy" fracture.

Examination for Size of Grain.—For this examination the sample must be well polished to remove all scratches due to grinding, and Stead recommends etching with a 20 per cent. nitric acid solution. Ridsdale prefers to immerse the specimen for one or two minutes, in a half saturated solution of iodine in alcohol, and the author has obtained very good results with Sauveur's method of dipping in strong nitric acid and then washing in a stream of water. Any of the above methods of etching will give good results for this purpose, and after well washing in water and spirit the sample is ready for examination. Both oblique and vertical illumination should be used, and comparatively low powers are required, a magnification of from 50 to 100 diameters generally being quite sufficient, or in cases of exceptionally coarse structures a much lower magnification. Such an examination will generally reveal any coarse crystallisation, and will often give a clue as to the heat treatment to which the steel has been subjected, which must be confirmed by further examination under higher powers. As the size of the grain will vary with the heat treatment it is often important to measure this, and keep a record for reference to compare with similar sections. The simplest way of doing this is to use a micrometer eyepiece, as the average diameter of the grains can then be read off direct from the microscope. Another plan is to take a photograph of the sample at a given magnification and afterwards photograph the divisions of a stage micrometer slide at the same magnification, and place the photograph of the slide over that of the sample when the size of grain is readily obtained. A third method is to use a camera lucida with the microscope and go over the image with a planimeter and thus obtain the grain measurement. In drawing conclusions from the size of grain in any piece of steel the sectional area of the steel

sample must be carefully considered, as it is the relation to this sectional area rather than the absolute size of the grain which is important.

Examination to Determine Microstructures.—This examination is by far the most difficult, as it involves the identification of various microstructures and constituents, and where these are not clearly defined, or where they merge the one into the other, considerable experience is necessary to determine the exact structure and distinguish the particular constituents. In preparing the sample, it is polished and etched by one of the methods described and mounted upon a slide with some plastic material. As a rule, direct illumination is best for this examination, and high powers are in many cases necessary, some structures not being resolved under 1,000 diameters, while for others 1,500 diameters are desirable, although for most work a magnification of 500 or 600 diameters is sufficient.

The only way to acquire an exact knowledge of the microstructure of steel is to carefully prepare specimens until the student can readily identify the chief constituents and structures, and so gradually gain experience, no amount of examination of photographs giving him the necessary knowledge. The following are the four chief microstructures which are now fully recognised, viz.:—Ferrite, Cementite, Pearlite, and Martensite, and some of these are usually found in all steels, whether quenched or unquenched.

There are three other Carbon conditions identified by the microscope—viz., Sorbite, Troostite, and Austenite—which are found only in steels within certain limits of composition, and which have been subjected to special heat treatment.

Ferrite (the name suggested by Howe for the crystals of practically pure iron, or, as Sorby calls it, free iron) is the chief constituent of soft steel that has been slowly cooled, or quenched below the critical point, Ar_1. It is described as crystallising in polyhedric grains, which are interfering crystals of the isometric system, mostly cubes and octahedra. On etching the polished surface of a nearly carbonless iron with a solution of iodine or nitric acid, or, better still, picric acid in alcohol, it will be found that the Ferrite remains white and brilliant, or takes only a slightly mottled appearance. On polishing a steel, the Ferrite, being softer than the other constituents, wears away sooner, so that the final result leaves the other constituents of the steel standing in relief on the worn-down Ferrite. This constituent in the *free state* is practically absent from steels containing above ·9 of Carbon.

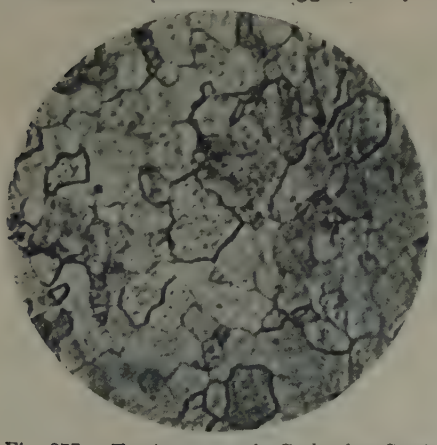


Fig. 277.—Ferrite or nearly Carbonless Steel. Magnification, 150 diameters. The junctures of the Ferrite grains are clearly shown, and this is characteristic. In some cases Ferrite appears as a white body, no junctures being visible, when the surface is only slightly etched.

It must be remembered that these Ferrite crystals, although they have the appearance of, are not necessarily pure iron, but may contain Silicon, Phosphorus, &c., in fact, any metalloids or impurities in the steel except Sulphur and Carbon, which do not appear to penetrate the Ferrite. Fig. 277 is a photograph of steel containing ·057 per cent. of Carbon, and consists almost entirely of Ferrite.

Cementite.—This constituent is undoubtedly a Carbide of Iron, and its composition would appear to be expressed by the formula Fe_3C. It occurs in bands, or segregated masses in high Carbon steel, is intensely

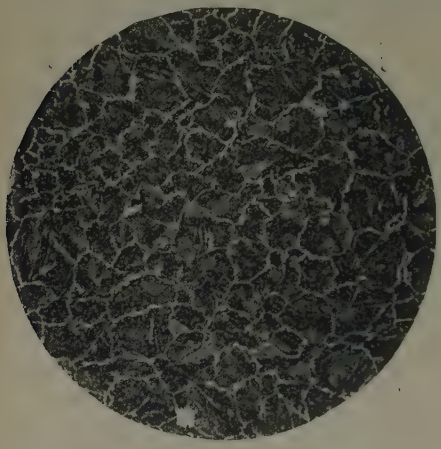


Fig. 278.—Steel containing 1·306 per cent. of Carbon. Magnification, 150 diameters. The white thread-like bands surrounding the dark areas are the Cementite.

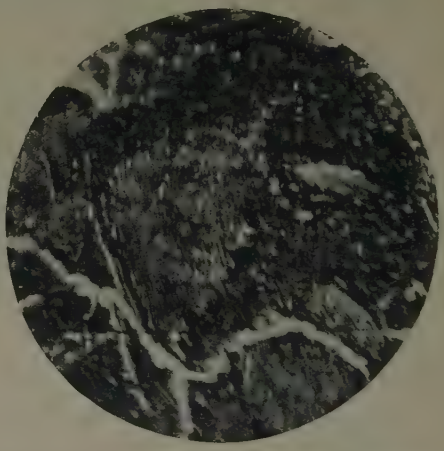


Fig. 279.—Same as 278. Magnification, 1,500 diameters. This shows the white bands of Cementite much enlarged, and that the dark areas which they more or less surround are laminated Pearlite.

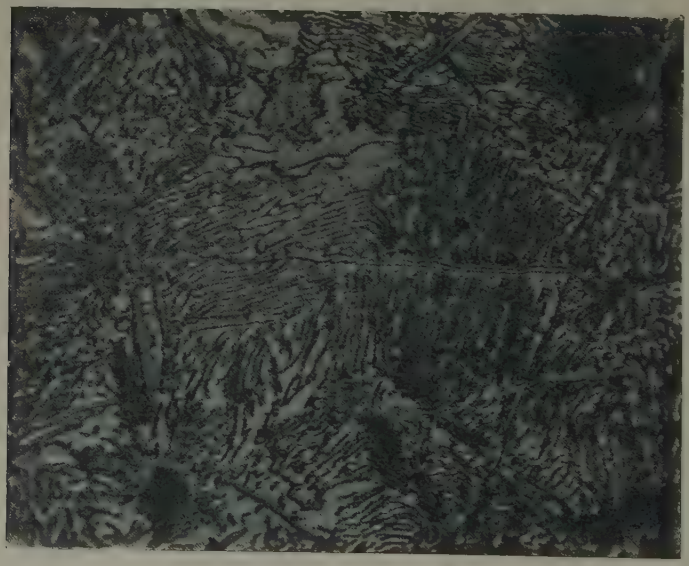


Fig. 280.—Another high Carbon steel showing the Cementite segregated in masses associated with Pearlite. The white raised portions are Cementite, the dark laminated portions Pearlite. Magnification, 1,000 diameters.

brilliant by direct illumination under the microscope, but perfectly black by oblique illumination. It often occurs as thin bands surrounding the Pearlite

grains. It is intensely hard, and remains bright even after repeated attacks with iodine, nitric acid, or picric acid. It cannot be scratched by a needle, whilst Ferrite can. This constituent is abundantly present in high Carbon, unhardened steel, but is practically absent in the *free state* from steel containing under ·9 per cent. of Carbon.

It is not necessarily pure Carbide of Iron, but may contain other Carbides present in the steel. Figs. 278, 279, and 280 are characteristic photographs of Cementite as it appears under low and high powers respectively.

Pearlite is an intimate mixture of Ferrite and Cementite. It occurs in two varieties—the lamellar and the granular. The lamellar, or laminated, so-called because it is made up of very thin plates or lamellæ of Ferrite and Cementite alternately, is found in steel very slowly cooled from a high temperature, and especially in annealed steel. It takes its name from the play of colours seen after etching, suggestive of mother-of-pearl. The granular variety consists of a mixture of irregular grains of Cementite and Ferrite, chiefly found in steels which have been reheated to a low temperature; the Pearlite in steel annealed at just under Ar_1 is granular. Pearlite appears to be practically the sole constituent of unhardened steel, containing from ·8 to ·9 per cent. of Carbon. It is generally coloured dark by iodine and by nitric acid, due probably to the presence of Sorbite.

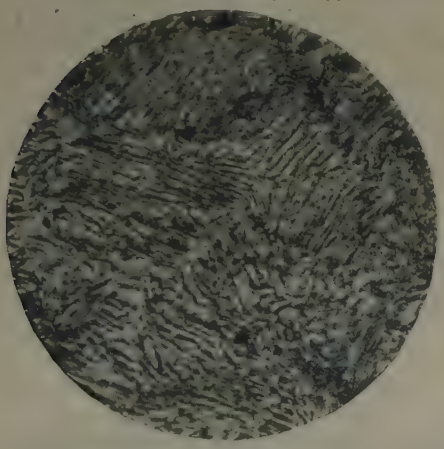


Fig. 281.—Steel containing ·871 C. Magnified, 1,500 diameters. Showing typical structure of laminated Pearlite.

Fig. 281 is a photograph of steel containing ·87 per cent. of Carbon under a high power, showing the typical structure of laminated Pearlite.

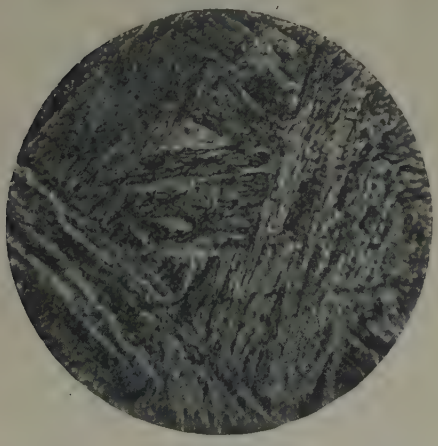


Fig. 282.—Steel containing ·468 C quenched from a temperature of 820° C. in water at 15° C. consisting entirely of Martensite. The interlacing crystalline structure is characteristic of Martensite.

Martensite. — This is the microstructure which is characteristic of steels quenched suddenly from high temperatures. Under the microscope it appears like a system of interlacing crystalline fibres. The real composition of Martensite is unknown.

On quenching small samples of steels containing from ·2 to ·8 per cent. of Carbon from above Ar_3, the structure apparently consists entirely of Martensite. It is developed and coloured by iodine and by nitric acid, the

intensity of the colour increasing with the percentage of Carbon in the steel. It is also developed by Liquorice infusion or Ammonium Nitrate. Martensite with the maximum amount of Carbon is called Hardenite, so that a quenched steel containing ·9 per cent. of Carbon, consists entirely of Hardenite.

Fig. 282 is a photograph of a Carbon steel under a high power and shows the general appearance of Martensite.

Sorbite.—This is a transition product between Martensite and Pearlite, or, to be more precise, between Troostite and Pearlite in unhardened steel, and Cementite and Martensite in hardened steel. It is obtained, according to Osmond,* by cooling sufficiently slowly to allow the transformations to take place only partially, and yet with sufficient rapidity to produce an imperfect separation of Ferrite and Cementite. In practice these conditions are more or less fulfilled by cooling small samples in air, by quenching in cold water towards the end of the recalescence, by quenching in lead, or by reheating or tempering Martensite at a temperature under 600° C. It may almost be regarded as unsegregated Pearlite. Under the microscope it is characterised by the absence of striæ, and by the rapidity with which it is coloured by "polish attack," or by tincture of iodine and picric acid.

Troostite represents a transition Carbon condition between Martensite and Sorbite. According to Osmond, if a piece of steel containing about 0·85 per cent. of Carbon be quenched in cold water during the recalescence, the grains which have undergone transition consist of Pearlite, those untransformed of saturated Martensite, while between these two all degrees of transformation can be detected. Troostite may be produced (1) by sudden cooling of steel during the recalescence period; (2) by a mild quenching of small pieces (in oil or boiling water), or of small pieces from a temperature higher than that of the critical range; or (3), by a mild tempering of Martensite.

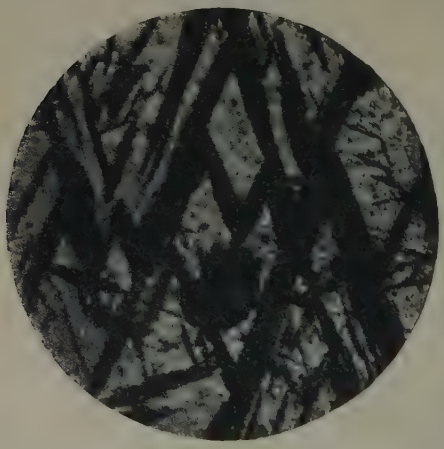


Fig. 283.—Sample of Steel containing 1·6 per cent. of Carbon quenched in Ice Brine from 1,100° C. The light ground mass is Austentite, and the dark barb-like structure Martensite or Hardenite.

Osmondite.—It has recently been proposed to use the name Osmondite for the structures representing the intermediate stages between Martensite and Pearlite, and for those found in hardened steels which have been tempered, and to omit the names Sorbite and Troostite.

Austenite.—This has no well-defined structure, and represents an unknown Carbon condition. It is produced in maximum quantity by the very sudden cooling of steel containing about 1·5 per cent. of Carbon from a temperature above 1,000° C. It is softer than the surrounding Martensite, and can be scratched with a needle or with Apatite. On treating with ammonium nitrate it remains uncoloured, and can thus be distinguished from Martensite. The scratching test the author has found very difficult to carry out, but the treatment with ammonium nitrate is characteristic.

* *Metallographist*, vol. i., No. 2, p. 152.

PLATE XVIII.—Microstructure of Quenched Steel.

[To face page 464.

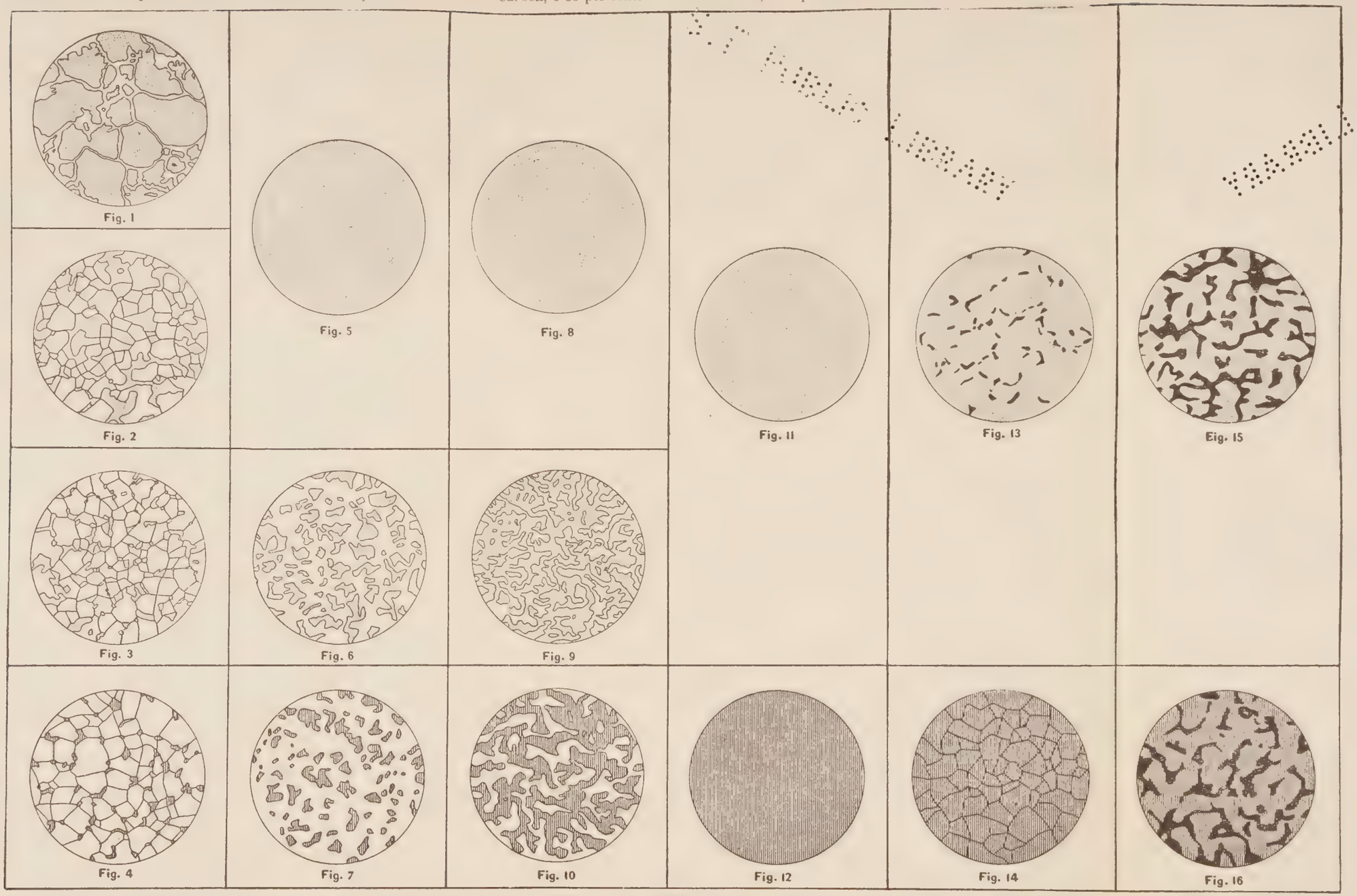


Fig. 284.—Diagrammatic Illustration of Microstructure of Steel, quenched above, between, and below the Critical Points.

It follows from the foregoing definitions that the proportion of Ferrite to Pearlite, Cementite, and Martensite in any given sample of steel depends upon the percentage of Carbon in the steel, and on the heat treatment. Thus, a sample of steel containing about ·9 per cent. of Carbon on slow cooling consists almost, if not entirely, of Pearlite, but on rapid quenching in water from a high temperature becomes wholly Martensite, and any intermediate treatment between these two extremes produces a corresponding alteration in the structure and Carbon condition. Again, in normally cooled steels, structurally free Cementite is never found in specimens containing less than ·9 per cent. of Carbon, but above this point it gradually increases with the percentage of Carbon, provided the steel is unhardened, whereas, on hardening by quenching, both the Cementite and Pearlite are largely converted into Martensite. In unhardened pure Carbon steels containing from ·1 to ·9 per cent. of Carbon the steel consists entirely of Ferrite and Pearlite, the Ferrite decreasing and the Pearlite increasing with the percentage of Carbon. Above ·9 per cent. of Carbon unhardened steels consist of varying mixtures of Pearlite and free Cementite. From the composition of Cementite and Pearlite, Sauveur * has calculated the proportions of Ferrite, Pearlite, and Cementite present in unhardened steels, and the following table by him gives approximately the proportions of these constituents in steels of different compositions :—

TABLE CIX.—Theoretical Microstructural Composition of Unhardened Carbon Steels.

Carbon per cent.	Microstructural Composition per cent.			Carbon per cent.	Microstructural Composition per cent.		
	Pearlite.	Ferrite.	Cementite.		Pearlite.	Ferrite.	Cementite.
...	...	100	...	1·30	91	...	9
0·10	12	88	...	1·40	90	...	10
0·20	25	75	...	1·50	88	...	12
0·30	37	63	...	1·60	86	...	14
0·40	50	50	...	1·70	85	...	15
0·50	62	38	...	1·80	83	...	17
0·60	75	25	...	1·90	81	...	19
0·70	87	13	...	2·00	80	...	20
0·80	100 †	...	...	2·10	78	...	22
0·90	98	...	2 †	2·20	76	...	24
1·00	97	...	3	2·30	74	...	26
1·10	95	...	5	2·40	73	...	27
1·20	93	...	7	2·50	71	...	29

These figures do not profess to an approach to absolute accuracy, but they are a very useful guide, and will be found very nearly to agree with the results obtained on the actual examination of samples.

Sauveur in the same paper published the results of a very complete series of experiments on the influence of quenching from temperatures above and below the critical points on the microstructure of Carbon steels, and the following table, which is compiled from very careful measurements of the areas of the different constituents, is a summary of the results obtained.

* "Microstructure of Steel," *Amer. Inst. of Min. Eng.*, Sept., 1896.

† The latest research has shown that ·9 Carbon gives 100 per cent. Pearlite, and free Cementite does not appear till this is exceeded.

It will be seen that the temperature has a very marked effect upon the structure. Steels containing from ·21 to ·8 per cent. of Carbon when quenched above Ar_3, or between Ar_2 and Ar_3, consist of Martensite, but when quenched below Ar_1 they contain a large proportion of Pearlite, in fact have the structure of slowly cooled steels. This is what we should anticipate, as the change from hardening Carbon to Cement Carbon, or, in other words, from Martensite to Pearlite, which are the structures which correspond to this Carbon change, is complete when Ar_1 is reached; rapid cooling below this temperature has no influence either on the Carbon condition, or on the microstructure.

By the courtesy of Mr. Sauveur I am able to reproduce (fig. 284) diagrammatic representations of the microsections from which the following table was calculated. These explain the changes taking place far more clearly than any verbal description, and their careful study will well repay the student.

TABLE CX.—Microstructural Composition of some Quenched Carbon Steels.

Steel No.	Carbon per cent.	Quenched above Ar_3. Per cent. in Volume.			Quenched between Ar_3 and Ar_2. Per cent. in Volume.			Quenched between Ar_2 and Ar_1. Per cent. in Volume.			Quenched below Ar_1, or Slowly Cooled. Per cent. in Volume.		
		Martensite.	Ferrite.	Cementite.	Martensite.	Ferrite.	Cementite.	Martensite.	Ferrite.	Cementite.	Pearlite	Ferrite	Cementite.
1	0·09	77	23	...	27	73	...	11	89	...	10	90	...
		Quenched above Ar_2. Per cent. in Volume.											
		Martensite.		Ferrite.		Cementite.							
2	0·21	100		...		...		31	69	...	23	77	...
3	0·35	100		...		...		56	44	...	50	50	...
		Quenched above Ar_1. Per cent. in Volume.											
		Martensite.		Ferrite.		Cementite.							
4	0·80	100		...		...					100	...	...
5	1·20	94		...		6					92	...	8
6	2·50	80		...		20					77	...	23

Sampling for Micro Examination.—When a sample of steel is being prepared for microscopical examination it is very important to cut the specimens from the steel section, so that it shall be fairly representative of the entire section. In many cases it may be necessary to cut sections from the outside, the centre, and intermediate between the centre and the outside. When it is not possible to do this a section from between the centre and the outside should, if possible, be taken. If the sample is taken

from the outside erroneous inferences may be drawn owing to local cooling of the surface, &c., while, if taken quite from the centre, other causes conduce to error. In all cases where a complete examination is desired it is essential to examine sections in three different planes—(1) a vertical transverse section; (2) vertical longitudinal section; (3) horizontal longitudinal section. During rolling or forging the grains of the steel are liable to be distorted and elongated in the direction of rolling, and unless both transverse and longitudinal sections are examined it is difficult to form a correct opinion as to the form of crystallisation or size of grain; also intrusions of slag, sulphide of manganese, or other foreign matter may either pass unnoticed or appear in an exaggerated form according as the section is transverse or longitudinal.

Before polishing samples which have been heated, either for annealing or quenching, great care must be taken that the surface is filed or ground off to an appreciable depth to make quite sure that all the oxidised surface is removed, otherwise most misleading deductions may be drawn.

The general effect of annealing from high temperatures is to produce a separation of the Pearlite into larger areas, and more complete development of this structure, but this is not so marked in the set of photographs given later as in some cases, since the bars were rolled at a fairly high temperature, and allowed to cool slowly in air.

Annealing for a short time at a moderate temperature, not exceeding 900° C., does not very largely increase the size of the grain, although it is distinctly noticeable in most of the steels of which photographs are reproduced, but prolonged heating at low temperatures or comparatively short heating at very high temperatures produces a very coarse grained structure. The effect of prolonged heating on the size of grain is well shown in photos. 54, 55, 56, and 57, the sample annealed in a slag ball being a very extreme case. Such large grained structures usually denote excessive heating, either for too long a time or at too high a temperature, but this is not always the case, such crystallisation sometimes being due to other causes, as in the case of the structure of cast steel, which has not been forged or rolled (photo. 46). A very marked case of coarse crystallisation, due to prolonged heating, has recently been brought to my notice by Mr. Stead, who kindly sent me a portion of a sample of 2-inch mild steel billet which was embedded in a furnace bottom in such a position that the temperature did not exceed 700° C., and was probably nearer 600° C.; on removal after one year the Ferrite grains were over $\frac{1}{2}$ inch in diameter, and the bar was excessively brittle. Such a steel, however, by suitable annealing would be restored to its original condition.

Overheated steel must not be confused with what is known as burnt steel—*i.e.*, a steel which has been heated to a point near that of incipient fusion, so that the crystals are actually separated from each other, thus breaking up the continuity of the mass. According to Stansfield,* "burning" is a segregation of Carbide of iron or other fusible alloy of lower melting point than the mass of the steel, to the intercrystalline joints, and this fusible alloy is afterwards more or less expelled, either by gases imprisoned in the steel, or by Carbon Monoxide formed by the Carbon in the steel, reacting on the scale formed on the steel. The gases in escaping produce blisters, and ultimately openings in the skin through which the fluid material at the joints of the crystals is expelled, leaving flaws or cavities which afterward become more or less oxidised. Such steel is brittle, and practically useless, and its original mechanical properties cannot be restored by any subsequent heat treatment.

* *Iron and Steel Inst. Journ.*, 1903, vol. ii.

Figs. 285 and 286 show the general appearance of "burnt steel" at a low and moderately high magnification.

So far microscopic examination has not enabled the percentages of Silicon, Sulphur, and Phosphorus in steel to be determined with any degree of accuracy when present in normal quantities. The presence of a considerable percentage of Manganese may generally be detected by its affecting the general structure of the steel. In such steels the size of the grain is usually larger, and the Pearlite tends to be granular rather than laminated. That Phosphorus in large quantities is easily detected has been shown by Stead in his exhaustive paper on "Iron and Phosphorus," * but the microscope

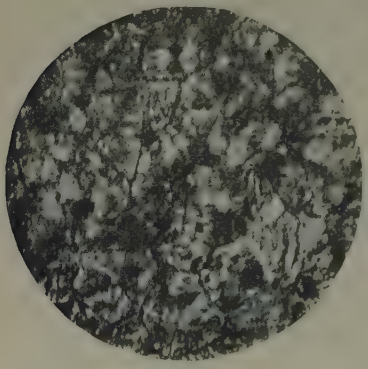


Fig. 285. – Magnification, 60 diameters. Burnt Steel, 2½-inch billet, which was "burnt" in the furnace. The grains are broken up, and junctions which appear as fine lines are shown under a higher power to contain Oxide.

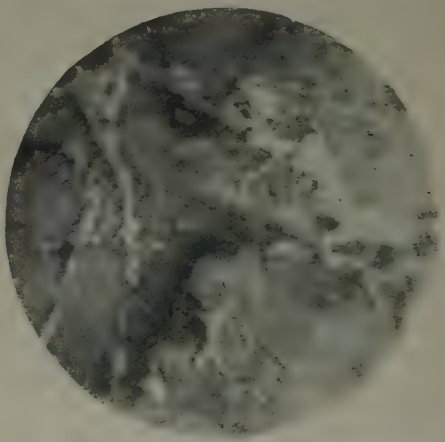


Fig. 286. —Magnification, 250 diameters. Burnt Steel, same as No. 459, showing the grains to be more or less surrounded by Oxide of Iron.

does not enable us to form a reliable opinion as to the amount present in the small proportions usually found in commercial steels. The heat-tinting, as developed by Stead, seems to offer the most promising results in this direction. Sulphides of Iron and Manganese can often be detected in steels under the microscope when present in small quantities, and both Prof. Le Chatelier and Prof. Arnold have shown as regards some special high Sulphur alloys that the Sulphide of Iron tends to form mesh-like structures round the grains of iron, which structure is to a large extent broken up by the addition of Manganese to form Sulphide of Manganese. Sulphide of Manganese in ordinary steel usually appears as little greyish globules, or small elongated cigar-shaped patches, according as a transverse or longitudinal section of the forged sample is examined, and a general opinion as to the steel being high or low in Sulphur can often be formed, but it is not possible to determine the actual percentage.

In the photographs given later, the structures of most of the steels, except the oil quenched and oil tempered, are fairly distinctly shown. They have been taken rapidly under the ordinary laboratory conditions, and are simply intended to give the student a general idea of the microstructure of different Carbon steels, such as he can observe himself. In the case of the oil

† *Iron and Steel Inst. Journ.*, 1900, vol. ii.

quenched and oil tempered sections, it is most difficult to distinguish in a *photograph* the Sorbite and Troostite structure, as in both cases they represent transition Carbon conditions in varying degrees of transformation, and it often is only by careful examination under the microscope and noting the effect of different etching media that the particular condition can be determined. The photographs given, so far as the author's experience goes, are typical of the structures of oil quenched and oil tempered steels, when such quenching has been carried out with small samples under the conditions specified; but at present little more can be said than that they consist of Pearlite, Ferrite, and Cementite, in various stages of transformation, and the terms Sorbite or Troostite structure are used in this sense. Many of the photographs at low power do not show any definite structure, but they are purposely given to show that certain structures are not defined under low power, and for comparison with the high power photographs. It is most important that the student should bear in mind the influence of mass on the microstructure of steel subjected to heat treatment, and he must not expect to get identical, or in many cases similar, structures to those given when treating 6-inch rounds, as it is clear that the rapidity of cooling of such a large mass would be very different to the rate of cooling of a small piece of $\frac{1}{2}$-inch round bar. Even the outside surface of such a large mass would be comparatively slowly cooled, owing to the conduction of heat from the centre, while the centre of the bar itself would be cooled still more slowly. This difference in structure is shown in photographs 58, 59, and 60 of sections taken from outside centre of an oil tempered axle.

The particular temperatures of oil quenching and oil tempering have been selected because they are those which are frequently used in everyday practice where oil tempering is employed on a large scale.

TYPICAL STEEL PLANTS.

PLATE XIX.—*Plan of the North-Eastern Basic Bessemer Steel Plant.*

PLATE XX.—*Plan of the Frodingham Basic Open Hearth Steel Works.*

PLATE XXI.—*Plan of Gary New Steel Plant.*

PLATE XXIa.—*Plan of the Normanby Park Steel Works.*

The various appliances for the manufacture of steel having been described in detail, the accompanying plans will enable the student to see how the different parts of the plants are disposed relatively to each other, and to trace the course of the metal through the various operations from the time it leaves the mixer, cupola, or blast furnace until it is ready to leave the works in the condition of finished bars, rails, angles, &c. The first two plans are typical of our average English works, which have been gradually altered to meet modern conditions; in neither case are they given as examples of latest design, and in fact since the plans were prepared very considerable alterations and improvements have been made in both works, with the object of increasing the output and reducing the labour costs; on the other hand, even as shown on the plans, the works are not far behind in leading essentials, so far as the converting and melting shops respectively are concerned, the plants are fairly up to date.

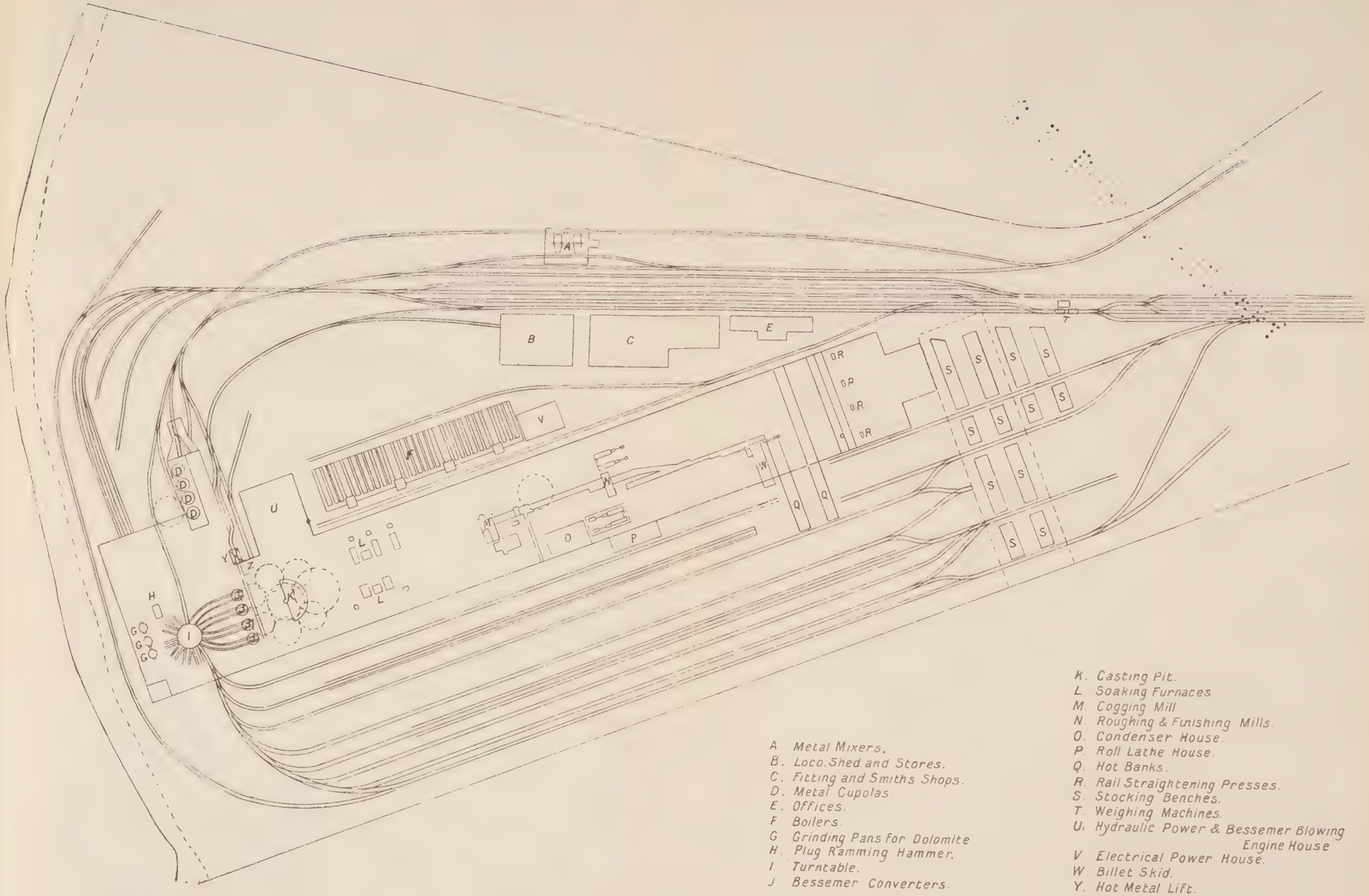
The Gary plant shows the arrangement of the largest and most modern up-to-date plant in America, and the Normanby Park plant, now being erected by Messrs. J. W. Lysaght, under the supervision of J. H. Darby, is representative of a medium sized English works, designed to meet modern requirements.

PLATE XIX.—Plan of North-Eastern Basic Bessemer Steel Plant.

[To face page 470.

This plant consists of four 15-ton basic Bessemer converters, J J J J, arranged in a line as shown, with an elevator track, Z, in front for the hot metal ladle to travel on. Part cupola and part mixer metal is used, and the ladle comes from mixer, A, or cupolas, D, along the railway shown to the lift, Y, by which it is raised to track, Z. The finished steel is poured from the converter into a ladle on a receiving crane, of which there are two, each serving a pair of converters. The receiving ladle full of metal is transferred to the jib of the centre casting crane, and the ingots are cast in the casting pit, K. The ingots are transferred from the casting pit to the soaking pits, L, from which they are conveyed by live rollers to the cogging mill, M, and then pass on to the roughing and finishing mill, N. In case of billets, they are transferred by the skid, W, to hot banks, Q, or in case of rails, to the straightening presses, R R R, and finally reach the stock benches, S S S. The entire works is encircled by several lines of rails communicating with the main line, so that raw material can be easily brought into, and finished material readily removed from, the works.

The basic shop is behind the converters, and tracks from each converter are connected with a large turntable, I, to facilitate the removal of old, and the replacement of new, bottom sections on the converter, and other repairs. There are three grinding mills, G, for grinding the basic material, and a plug-ramming machine, shown at H, for making the plugs for the bottom sections. The other details of the works will be understood from the lettering on the plate.



A. Metal Mixers.
B. Loco. Shed and Stores.
C. Fitting and Smiths Shops.
D. Metal Cupolas.
E. Offices.
F. Boilers.
G. Grinding Pans for Dolomite
H. Plug Ramming Hammer.
I. Turntable.
J. Bessemer Converters.

K. Casting Pit.
L. Soaking Furnaces
M. Cogging Mill
N. Roughing & Finishing Mills.
O. Condenser House.
P. Roll Lathe House.
Q. Hot Banks.
R. Rail Straightening Presses.
S. Stocking Benches.
T. Weighing Machines.
U. Hydraulic Power & Bessemer Blowing Engine House
V. Electrical Power House.
W. Billet Skid.
Y. Hot Metal Lift.
Z. Elevated Railway Track in front of Converters

Fig. 287.

PLATE XX.—Frodingham Basic Open Hearth Steel Works.

[To face page 470.

This plant consists of nine open hearth fixed furnaces, and two 100-ton Talbot furnaces; two of the small furnaces are being dismantled to make room for extension.

There are twenty-one producers of Dawson water-bottom type and several Talbot mechanically-poked producers, arranged in a line behind the charging side of the melting furnaces.

The pig metal is brought to the furnace in ladle direct from the blast furnaces, and lifted with an overhead electric crane and poured into the furnaces, the ore and lime are put in by means of a Wellman charger. On the tapping side there is also a ladle road the full length of the shop, and all the furnaces tap into ladles on carriages, and the metal is either cast in the straight pit in front of furnaces or transferred to a centre casting crane, and cast in the circular casting pit controlled by hydraulic radial cranes, as shown in the plan. The ingots are then taken to the soakers by steam travelling cranes, and from there to the live roller gear of the cogging mill. This mill is driven by a pair of reversing engines, geared 2 to 1 to the mill, and consists of one pair of rolls only. The piece travels through the cogging mill to the hot shears, and afterwards to an electric charger, which either puts it into the reheating furnace or transfers it to the finishing mill.

The finishing mill consists of three stands of housings, and is driven by a three-cylinder reversing engine; after leaving the finishing mill the bar is carried forward to the hot saw, and thence to the loading banks. The roller racks are driven by electric motors.

There is a range of fourteen Lancashire boilers mechanically stoked. There are several more steel furnaces than are shown in the plan, and, since the plan was prepared, one beyond furnace B has been dismantled to make way for the Talbot furnaces referred to.

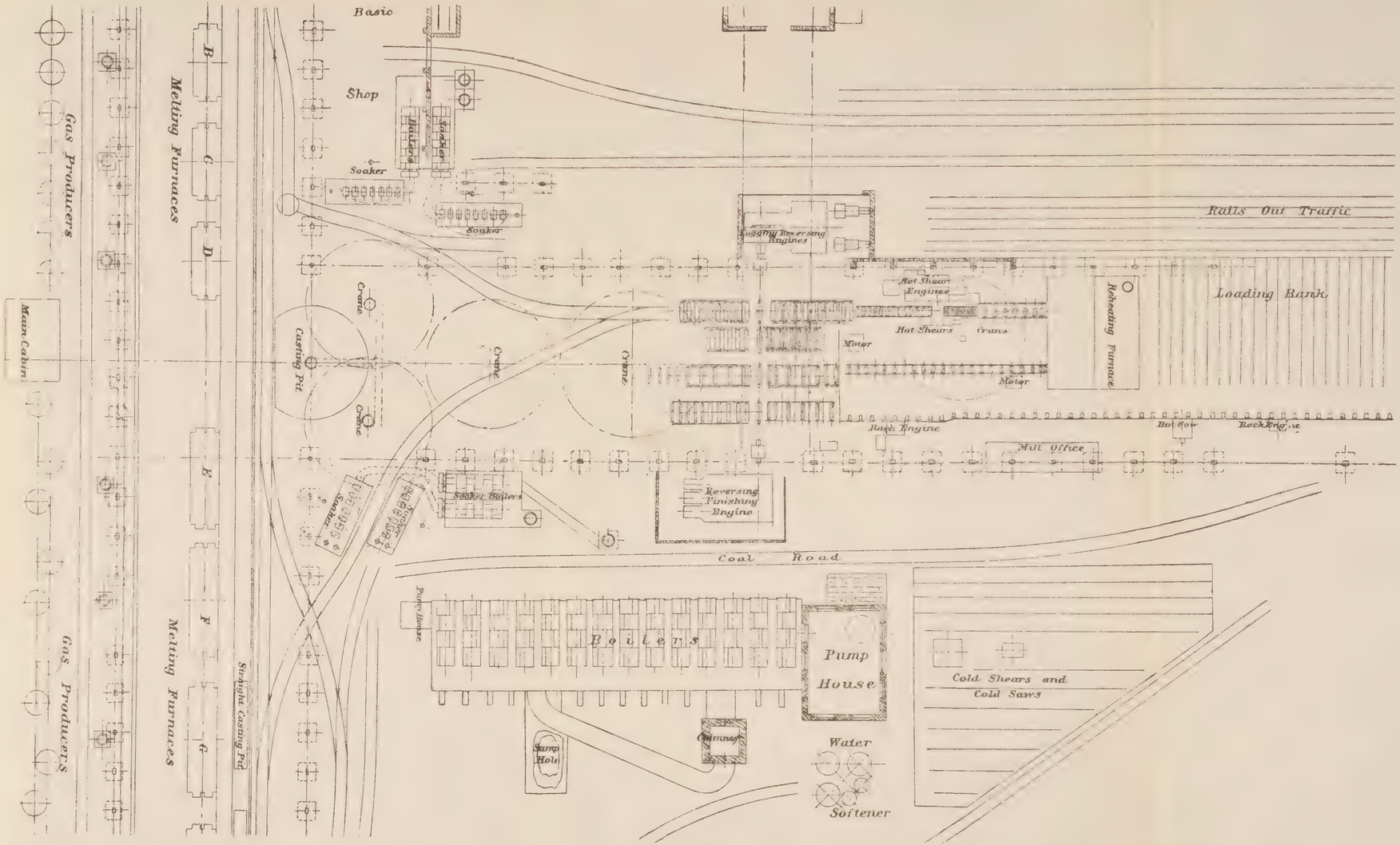

Basic
Shop
Soaker
Soaker
Rails Out Traffic
Loading Bank
Reheating Furnace
Hot Shears
Hot Shear Engines
Cranes
Motor
Motor
Rack Engine
Hot Saw
Rack Engine
Mill Office
Reversing Finishing Engine
Coal Road
Boilers
Pump House
Cold Shears and Cold Saws
Water Softener
Chimney
Sump Hole
Pump House
Main Cabin
Gas Producers
Gas Producers
Melting Furnaces
Melting Furnaces
Casting Pit
Crane
Crane
Crane
Crane
Soaker
Soaker
Soaker

PLATE XXI.—Plan of the New Gary Steel Plant.

[To face page 470.

Plan of New Gary steel plant, showing general arrangement of blast furnace and steel plants, and how the different parts of the plant are placed in relation to each other. To facilitate transport all the open hearth buildings are laid out in the skew, at an angle to the main North and South railway lines, so that all right angle curves in the different railway tracks are avoided. The entire plant covers about 1,000 acres, and that portion which deals with materials from the ore yard to the ingot stripper 300 acres. It is estimated that when completed the plant will be capable of producing over 4,000,000 tons of ingots per annum.

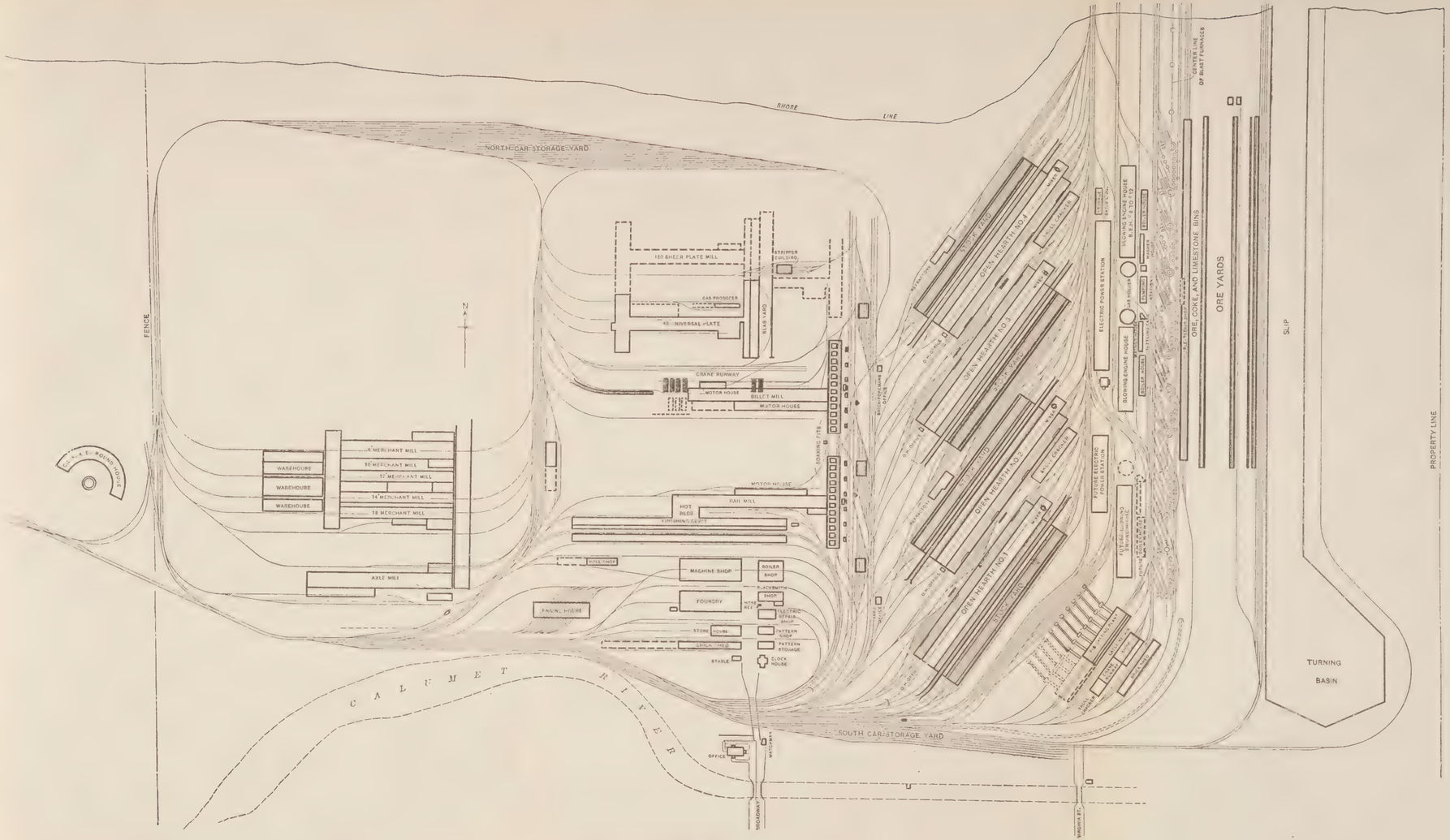


Fig. 289.

PLATE XXI*a*.—Plan of Normanby Park Steel Works

These works have been designed by Mr. John H. Darby, M.Inst.C.E., and are laid out so that they can be extended when desired.

The coke ovens are the Semet-Solvay continuous regenerative type, and the coal from the coal washery, after draining, will be compressed and charged into the ovens. A bye-product plant is to be attached for recovering tar, ammonia, and light oils, and there will be a large volume of surplus gas of high calorific value available for heating or other purposes in the works.

The blast furnaces are to be blown by gas engines with desiccated air; the waste gas from the blast furnaces is to be cooled, washed, and used for generating power by gas-engine driven generators, supplemented by mixed pressure steam driven turbine sets, utilising the intermittent waste steam from the mill engines; the exhaust steam from these engines is to be passed through a heat accumulator to regulate the flow to the turbines, supplemented when necessary with live steam. The electric current so produced is to be used for pumping and operating various parts of the plant, and the surplus balance of coke-oven and blast-furnace gases will be available for heating and other purposes.

The ores used will be obtained from the adjoining ore fields of the Frodingham district, which, although of low grade as regards iron contents, are easily mined in open faces, are nearly self fluxing, and contain sufficient manganese to produce a pig particularly suitable for conversion into soft steel by the basic open-hearth process.

The molten metal from the blast furnaces will be taken direct to a 400-ton capacity gas-heated metal mixer and afterwards to the basic open-hearth steel furnaces. These furnaces are served by overhead charging arrangements for handling liquid metal, ore, and limestone. The soft steel produced will be tapped from the furnaces into ladles, conveyed by an overhead crane to the casting stand and teemed into ingot moulds carried on trolleys. These trolleys carrying the ingots will be taken to the soaking pits and the ingots transferred direct into the soaking pits. The ingots will be removed subsequently to the mill driven by 3-cylinder reversing engines, and rolled down to bars of various sections.

The water supply will be derived from the river Trent and treated prior to use.

All sidings communicate with the Great Central Railway giving access to ports of shipment and elsewhere.

The phosphoric slag from the steel furnaces will be finely ground for manure.

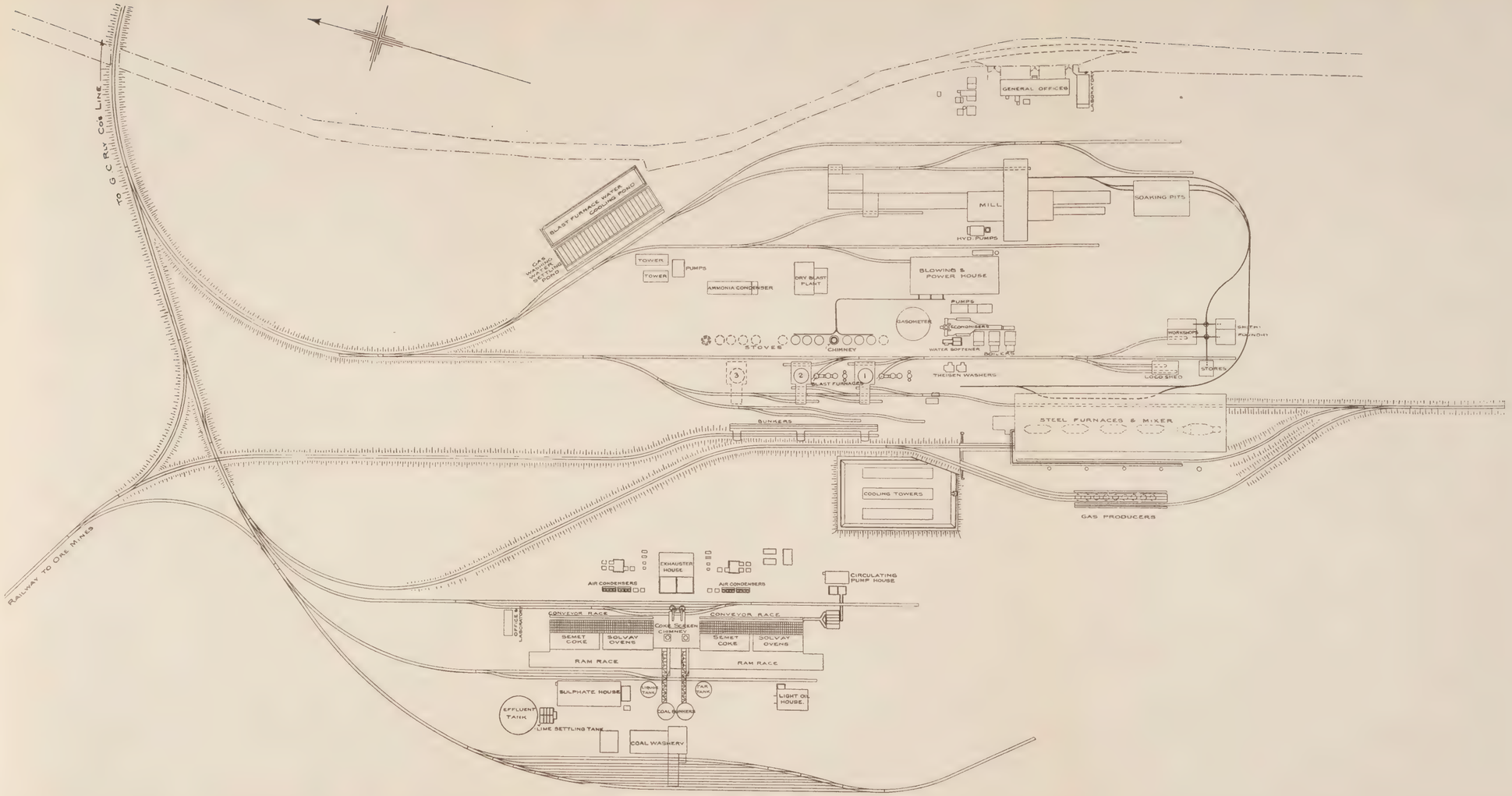


Fig. 289*a*.

PHOTO-MICROGRAPHS.

Explanatory Remarks.

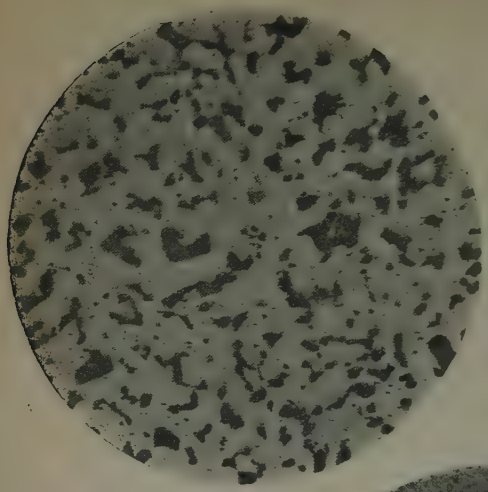
The following photographs, from 1 to 40, are from four steels containing respectively ·16, ·47, ·89, and 1·12 per cent. Carbon.

In each case photographs are given of the steels as annealed, water quenched, water quenched and reheated, oil quenched, and oil quenched and reheated, and in all cases both low and high power photographs are given. In most cases the photographs of the rolled, reheated, and water quenched are from the *same section*, it having been simply repolished and re-etched after each treatment. The oil quenched and oil tempered photographs are also from one section cut from the same bar as the rolled section.

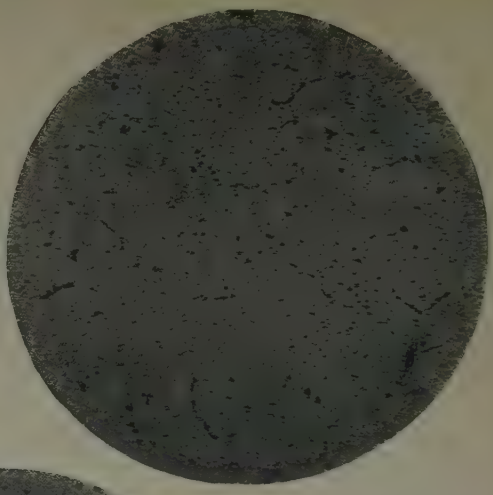
The other photographs are of a miscellaneous nature, and illustrate the effect of heat treatment, mechanical work, &c., particulars being given in each case.

The magnification was 100 and 1,000 for low and high powers respectively. All the photographs were taken with direct illumination.

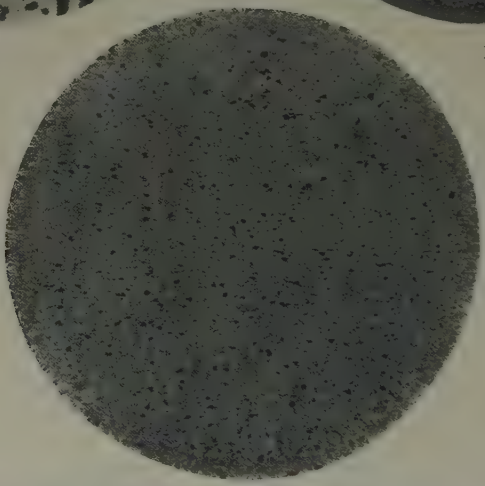
STEEL No. 1.—Magnification 100 Diameters. Carbon, ·16.



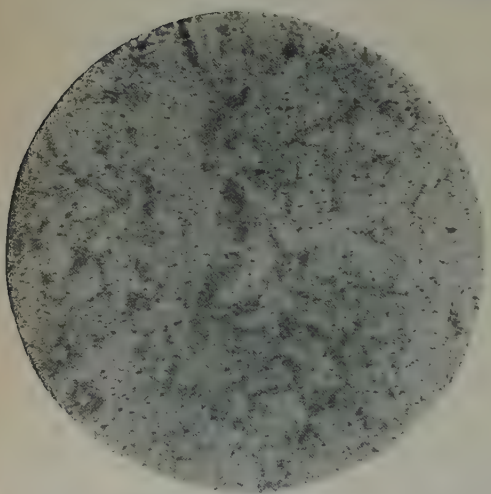
No. 1.—Annealed for 30 minutes at 900 C.; slowly cooled. Pearlite and Ferrite.



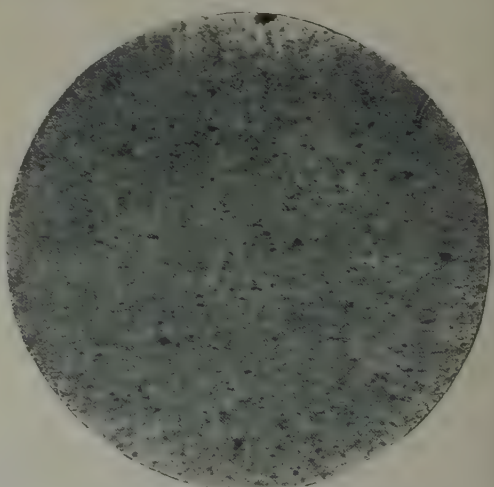
No. 2.—Heated to 900° C. for 30 minutes: water quenched from 900° C. Structure not resolved under this power.



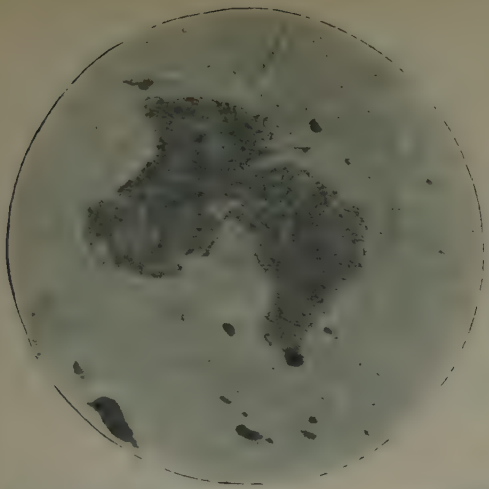
No. 3.—Heated for 30 minutes at 900° C. Water quenched from 900° C., and afterwards reheated to 450° C. Structure not resolved under this power.



No. 4.—Heated to 900° C. for 30 minutes; quenched in oil from 900° C. Confused structure not resolved under this power.

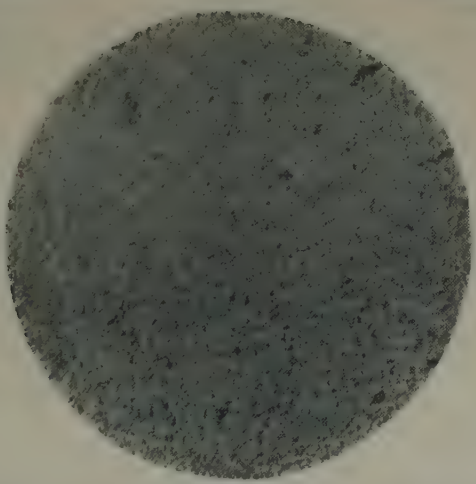


No. 5.—Heated to 900° C. for 30 minutes; quenched in oil from 900° C. and reheated to 450° C. Structure not resolved under this power.

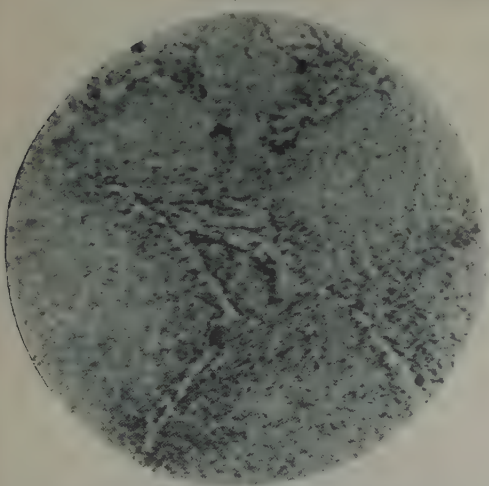


No. 6.—Same section as No. 1, at higher magnification. Annealed for 30 minutes at 900° C.; slowly cooled. Pearlite and Ferrite.

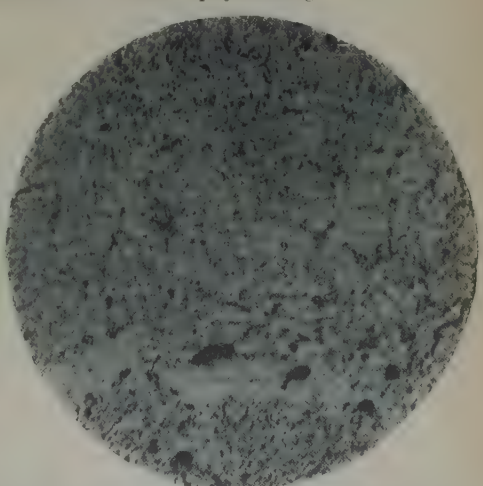
No. 7.—Same section as No. 2. Heated to 900° C. and water quenched. Martensitic structure.



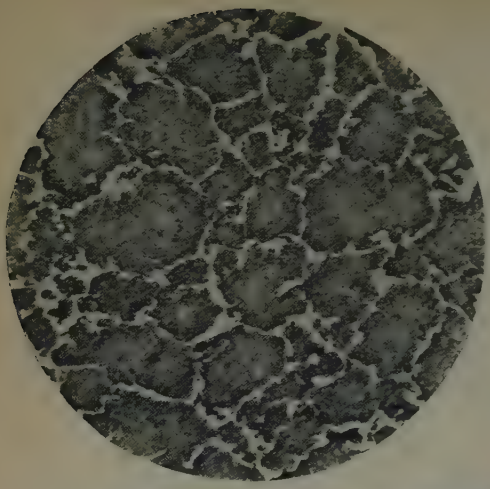
No. 8—Same section as No. 3. Reheated to 450° C. after water quenching. Structures not well defined, but shows how Martensitic structure in No. 5 is broken up by reheating.



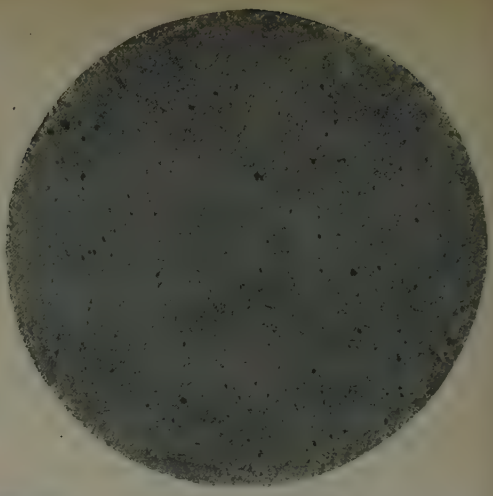
No. 9.—Same section as No. 4. Oil quenched from 900° C. Sorbitic structure.



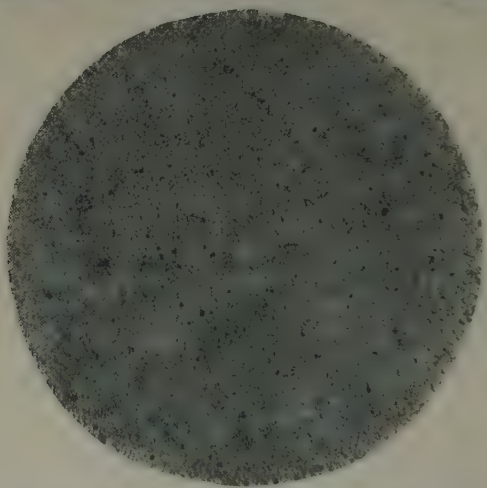
No. 10.—Same section as No. 5. Reheated to 450° C. after oil quenching from 900° C.



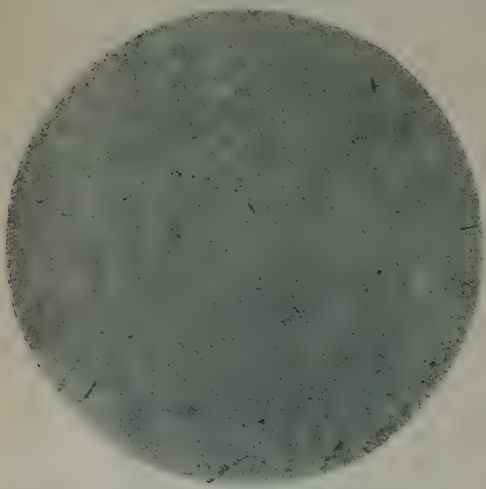
No. 11.— Annealed for 30 minutes at 900° C.; slowly cooled. Pearlite and Ferrite.



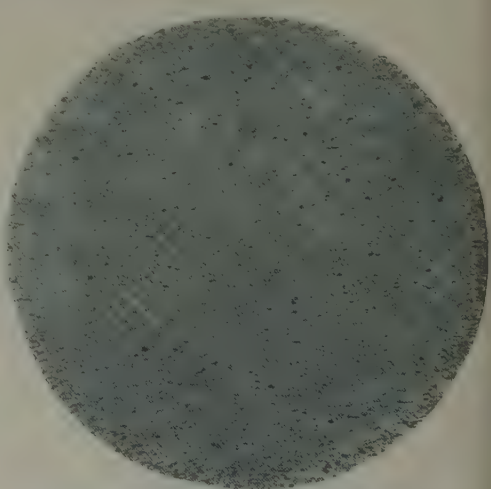
No. 12.—Heated to 900° C. for 30 minutes and quenched in water from 900° C. Structure not resolved under this power.



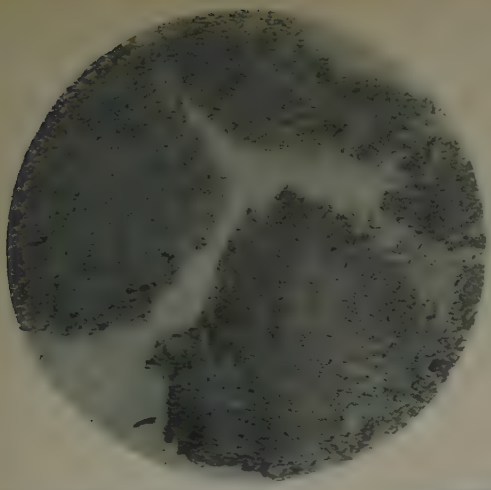
No. 13.—Heated to 900° C. for 30 minutes. Water quenched from 900° C. and afterwards reheated to 450° C. Structure not resolved under this power.



No. 14.—Heated to 900° C. and quenched in oil from 900° C. Confused structure not resolved under this power.

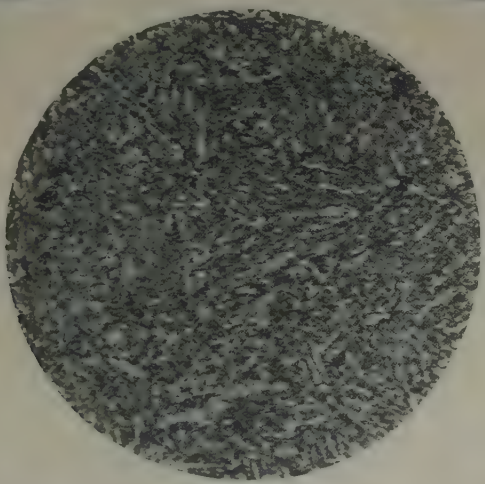


No. 15.—Heated to 900° C. for 30 minutes, quenched in oil from 900° C., and reheated to 450° C. Structure not resolved under this power.

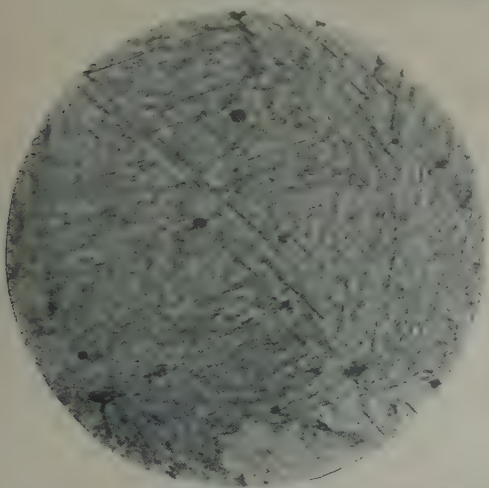


No. 16.—Same section as No. 11. Annealed and slowly cooled. Well-developed Pearlite and Ferrite.

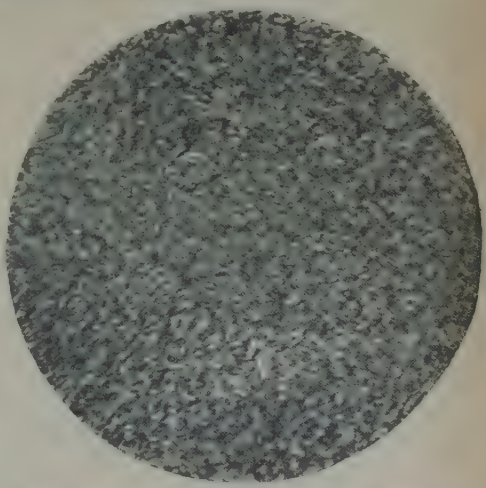
No. 17.—Same section as No. 12. Quenched in water from 900° C. Martensitic structure.



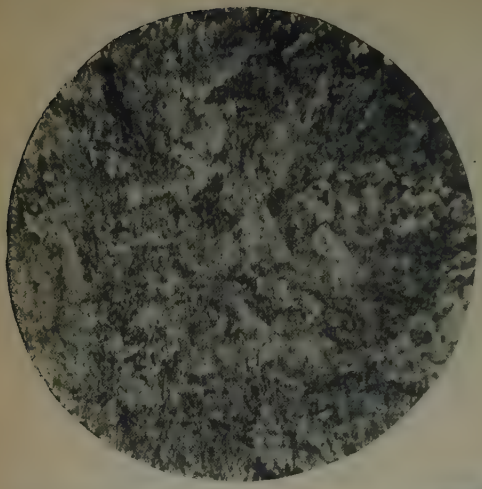
No. 18.—Same section as No. 13. Reheated to 450° C. after water quenching. Showing breaking up of Martensitic structure. Production of intermediate structure between Martensite and Pearlite.



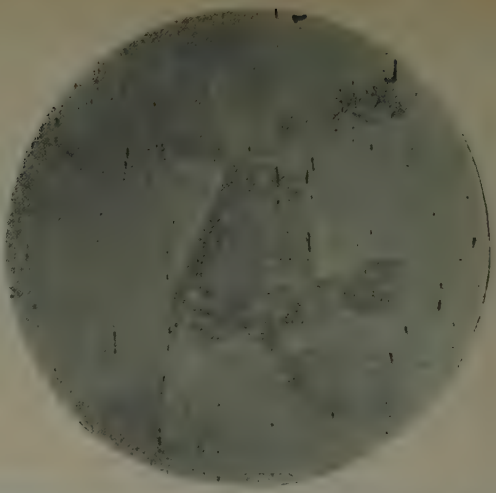
No. 19.—Same section as No. 14. Oil quench from 900° C. Structure intermediate between that shown in Nos. 17 and 18. Approaching Martensitic.



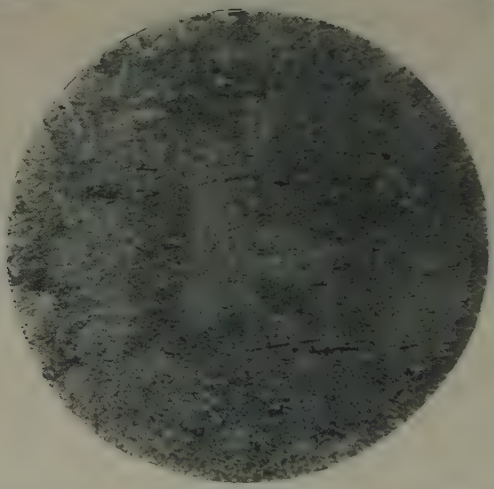
No. 20.—Same section as No. 15. Reheated to 450° C after oil quenching. Intermediate structure between Martensite and Pearlite, very similar to No. 18.



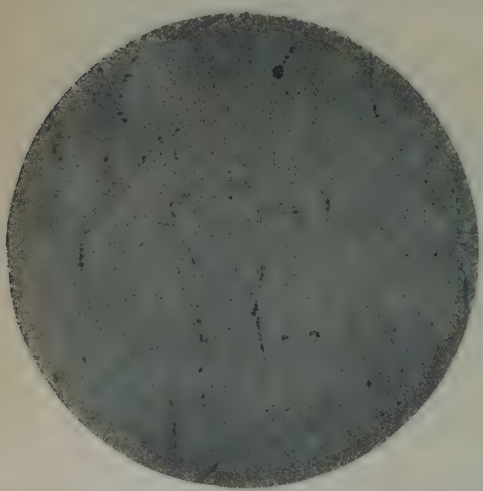
No. 21.—Annealed for 30 minutes at 900° C.; slowly cooled. Pearlite structure not resolved under this power.



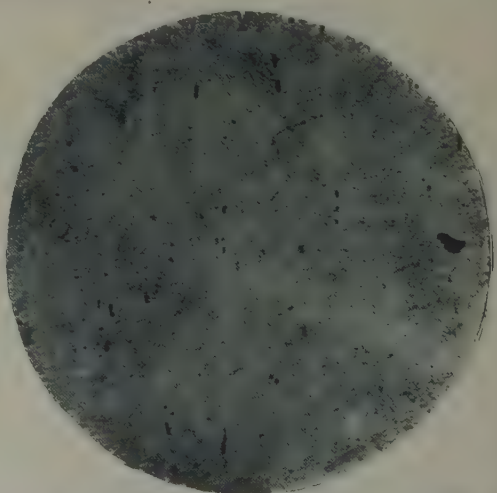
No. 22.—Heated to 900° C. for 30 minutes, and quenched in water from 900° C. Structure not resolved under this power.



No. 23.—Heated to 900° for 30 minutes. Water quenched from 900° C., and afterwards reheated to 450° C. Structure not resolved under this power.

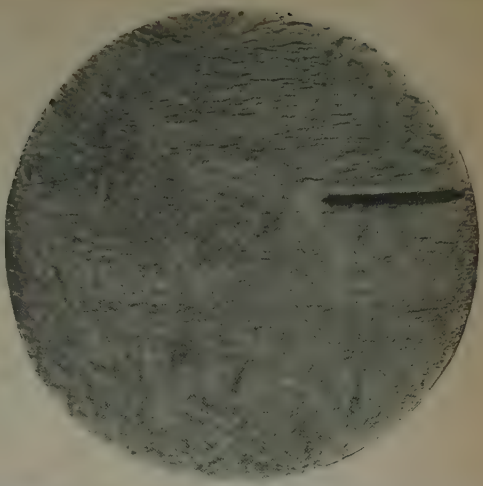


No. 24.—Heated to 900° C., and quenched in oil from 900° C. Confused structure not resolved under this power.



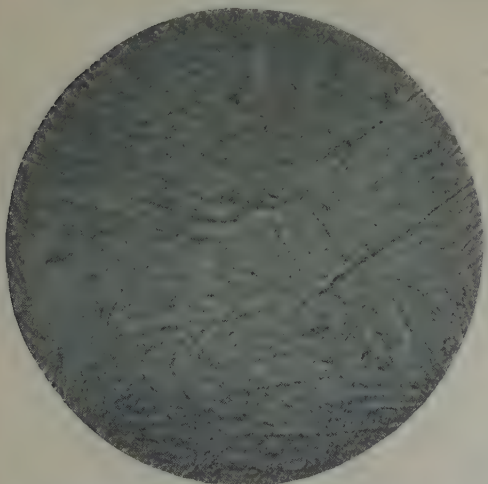
No. 25.—Heated to 900° C. for 30 minutes, quenched in oil from 900° C., and reheated to 450° C. Structure not resolved under this power.

No. 26.—Same section as No. 21. Annealed and slowly cooled. Well-developed Pearlite; saturated steel.

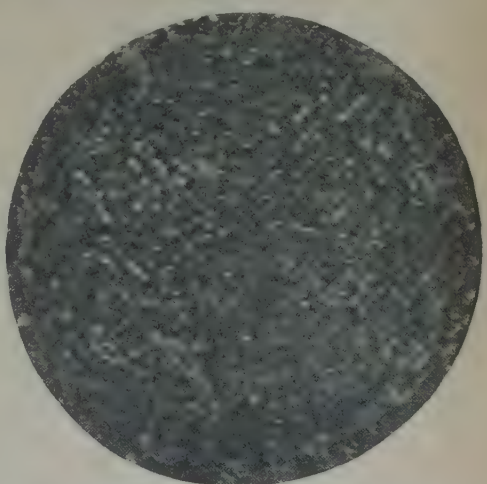


No. 27.—Same section as No. 22. Quenched in water from 900° C. Martensitic structure.

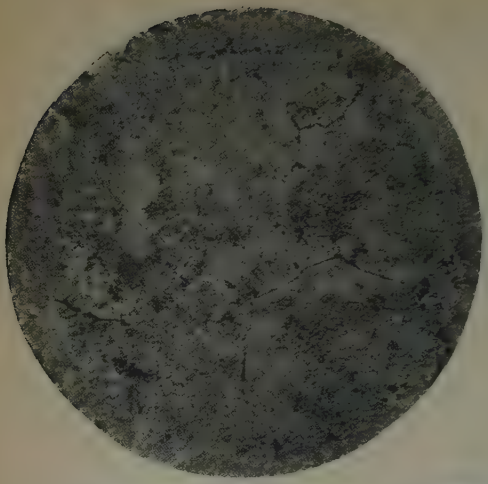
No. 28.—Same section as No. 23. Reheated to 450° C. after water quenching. Showing breaking up of Martensitic structure and production of intermediate structure between Martensite and Pearlite.



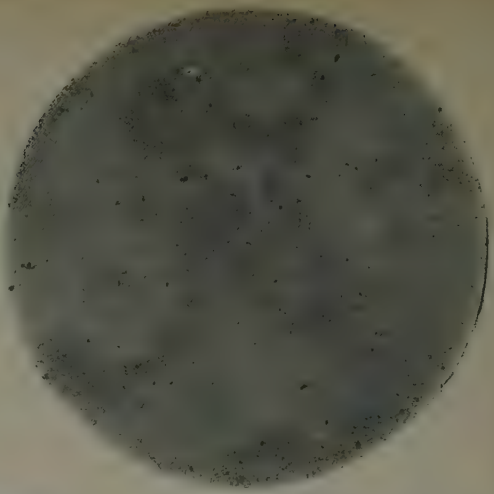
No. 29.—Same section as No. 24. Oil quenched from 900° C. Structure intermediate between that shown in Nos. 27 and 28. Approaching Martensitic.



No. 30.—Same section as No. 25. Reheated to 450° C. after oil quenching. Intermediate structure between Martensite and Pearlite, very similar to No. 28.

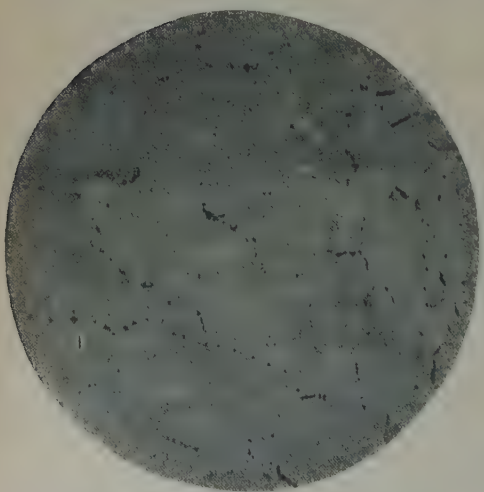


No. 31.—Annealed for 30 minutes at 900° C.; slowly cooled. Structure not clearly defined, but thin bands of Cementite just perceptible.

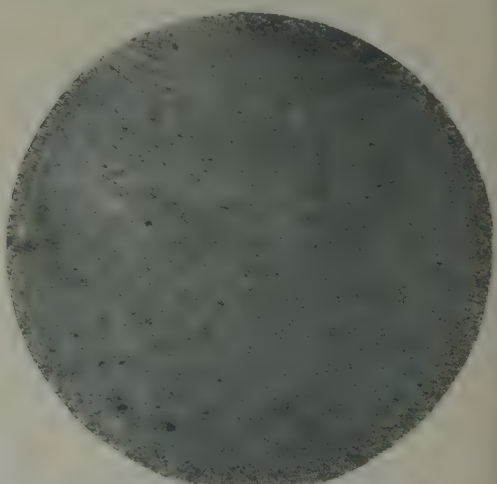


No. 32.—Heated for 30 minutes; water quenched from 900° C. Structure not resolved under this power.

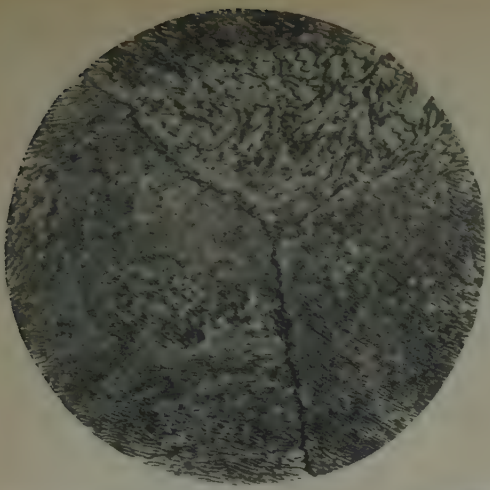
No. 33.—Heated for 30 minutes at 900° C.; water quenched from 900° C. and afterwards reheated to 450° C. Confused structure not resolved under this power.



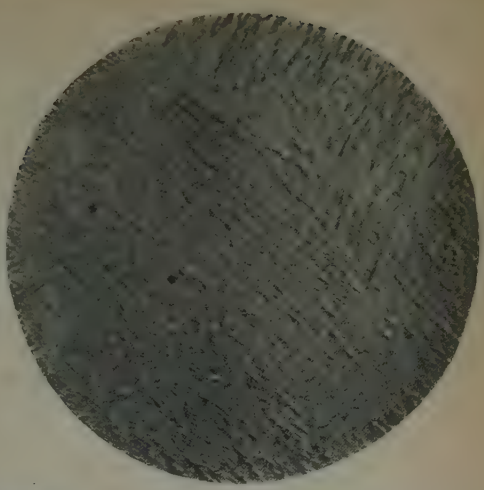
No. 34.—Heated to 900° C. for 30 minutes; quenched in oil at 900° C. Confused structure not resolved under this power.



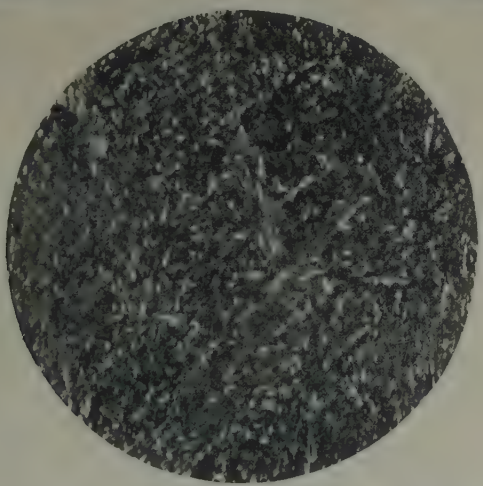
No. 35.—Heated to 900° C. for 30 minutes; oil quenched from 900° C. and reheated to 450° C. Confused structure not resolved under this power.



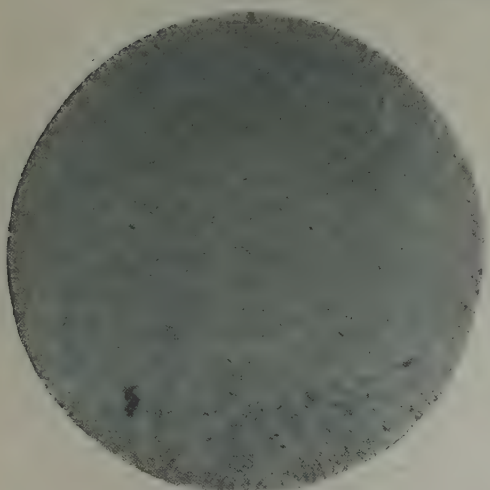
No. 36.—Same section as No. 31. Annealed to 900 C. Well-developed Pearlite and Cementite.



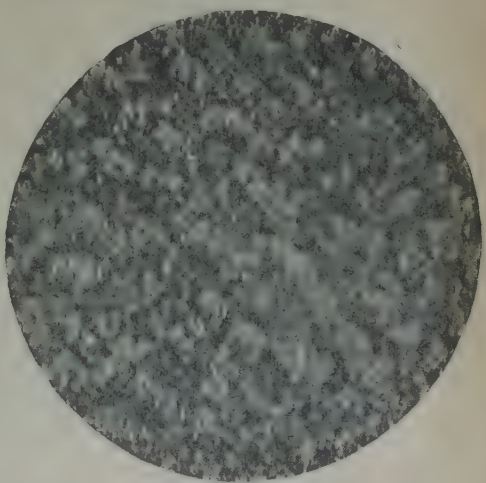
No. 37.—Same section as No. 32. Water quenched from 900° C. Martensitic structure.



No. 38.—Same section as No. 33. Water quenched from 900° C., afterwards reheated to 450° C. Intermediate structure between Pearlite and Martensite.



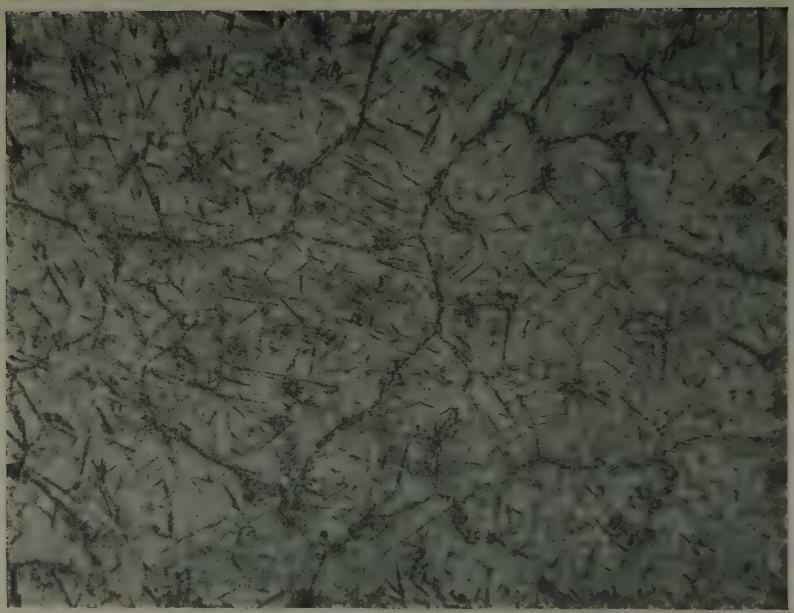
No. 39.—Same section as No. 34. Oil quenched from 900° C. Semi-Martensitic structure.



No. 40.—Same section as No. 35. Oil quenched from 900° C. and reheated to 450° C. Sorbitic structure.

HIGH CARBON STEELS.

1·5 per cent.

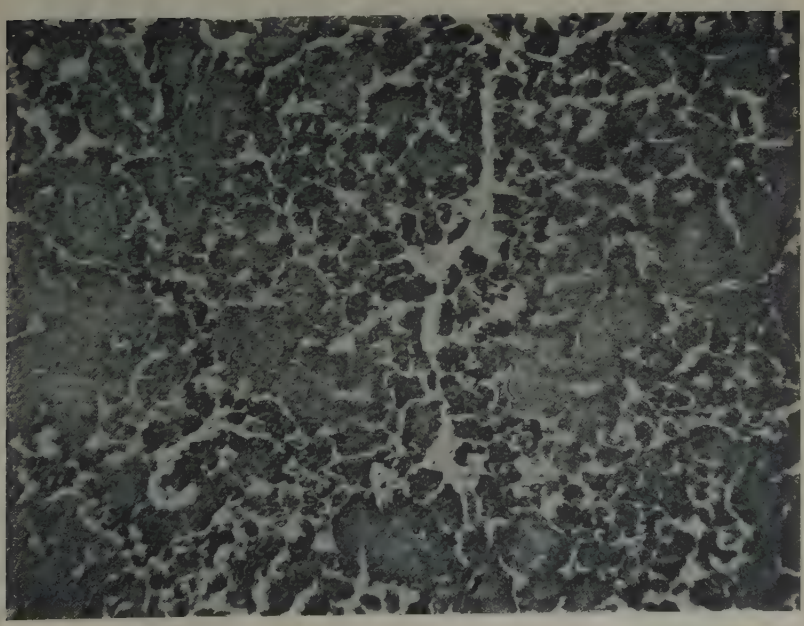


No. 41.—1·5 Carbon from ingot as cast. Magnification 100 diameters.

No. 42.—1·5 Carbon Steel from ingot, rolled and annealed. Typical structure, Pearlite with Cementite bands and some segregated Cementite. Magnification 1,000 diameters.

No. 43.—1·5 Carbon Steel from ingot, annealed; showing more segregated Cementite. Magnification 1,000 diameters.

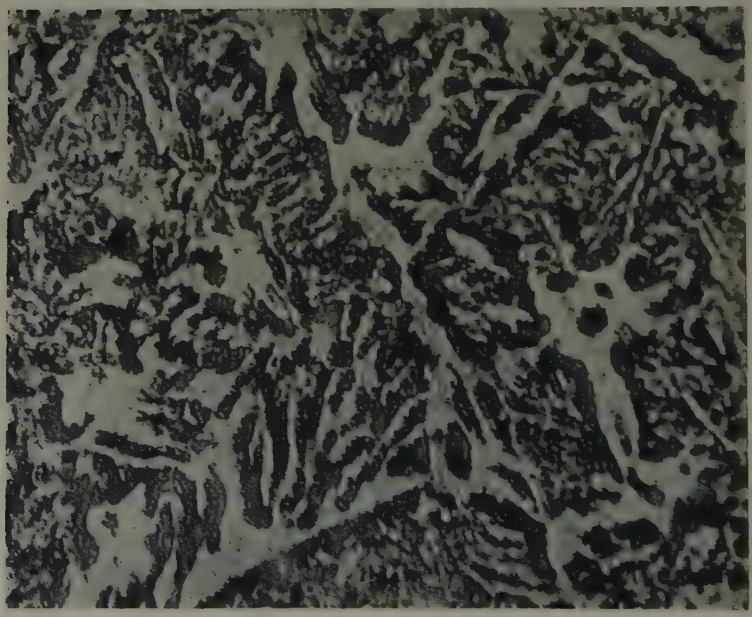
No. 44.—Steel Casting, as cast. Magnification 100 diameters.



No. 45.—Steel Casting, annealed. Magnification 100 diameters.

CAST STEEL.—Section showing original Microstructure.

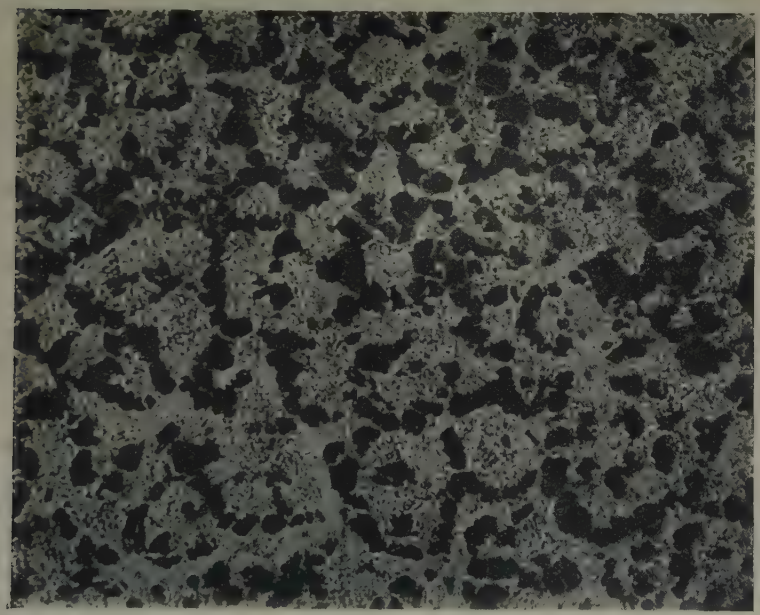
Carbon, 0·328 per cent.



No. 46.—As Cast. Magnification 100 diameters.

CAST STEEL.—Showing Effect of Annealing on Microstructure.

Carbon, 0·328 per cent.



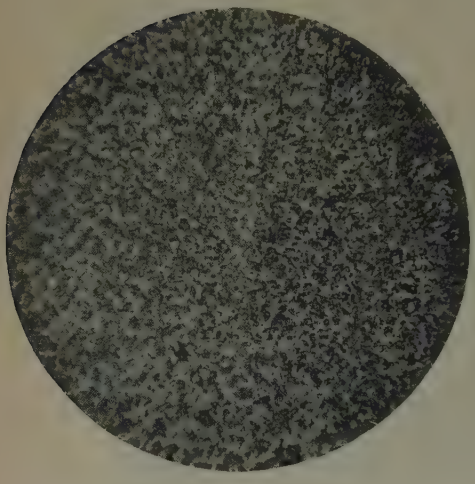
No. 47.—Same Section as 46, annealed at 900° for 20 minutes. Magnification 100 diameters.

PHOTOGRAPHS ILLUSTRATING CHANGES PRODUCED IN MICROSTRUCTURE AND MECHANICAL PROPERTIES BY HEAT TREATMENT. BARS 1½ ROUNDS. MAGNIFICATION 50 DIAMETERS.

ANALYSES

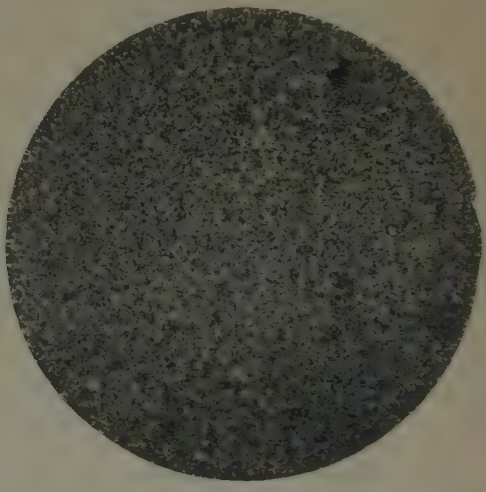
Carbon, 0·180; Silicon, 0·055; Sulphur, 0·055; Phosphorus, 0·071; Manganese, 0·500.

Microsections cut midway between centre and outside.



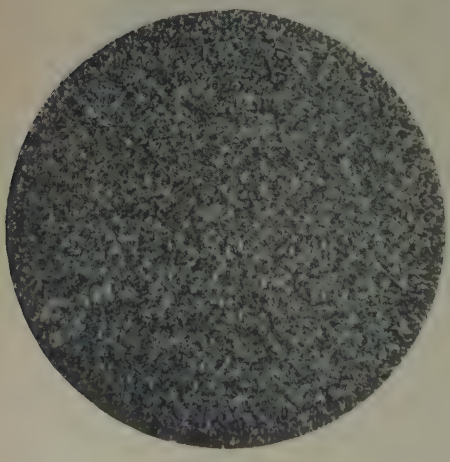
No. 48.—*As Rolled.*

Tensile stress, . . 29·8 tons per square inch.
Elastic limit, . . 15·1 ,, ,,
Elongation in 3 ins., . 33·3 per cent.
Reduction of area, . 57·6 ,,



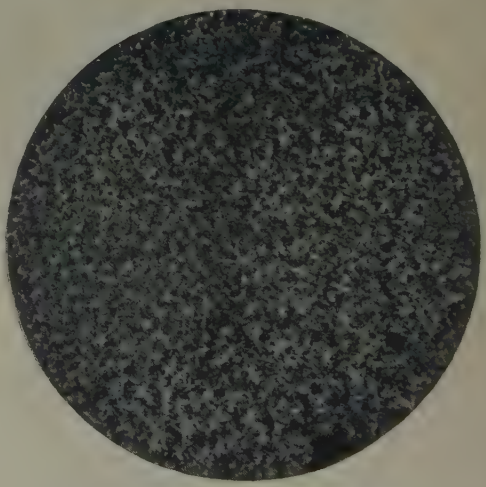
No. 49.—Heated to 740°-760° for 30 minutes, and cooled in ashes. Very fine structure, Ferrite and Pearlite intimately mixed.

Tensile stress, . . 29·0 tons per square inch.
Elastic limit, . . 15·2 ,, ,,
Elongation in 3 ins., 38·0 per cent.
Reduction of area, . 61·0 ,,



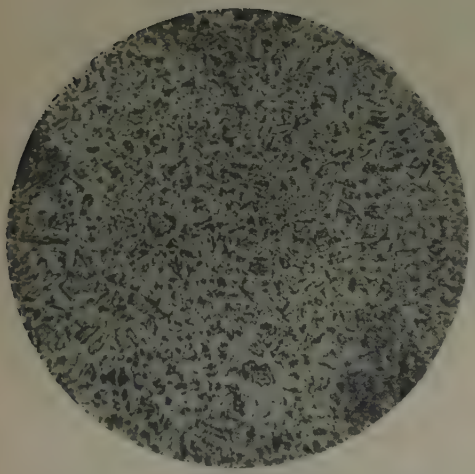
No. 50.—Heated to 820° for 20 minutes, and cooled in ashes. Structure not quite so fine as in No. 49.

Tensile stress, . . 29·1 tons per square inch.
Elastic limit, . . 14·7 ,, ,,
Elongation in 3 ins., 38·3 per cent.
Reduction of area, . 58·3 ,,



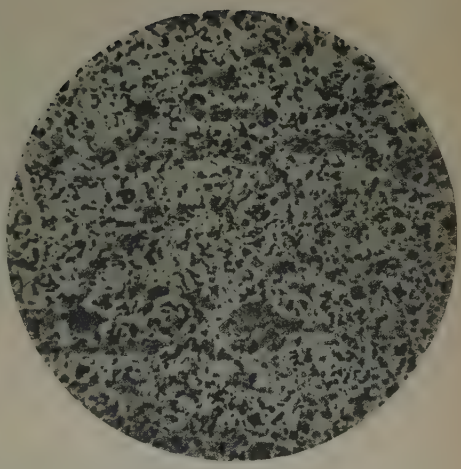
No. 51.—Heated to 820° for 1¾ hours. Structure slightly coarser than No. 50.

Tensile stress, . . 28·6 tons per square inch.
Elastic limit, . . 14·8 ,, ,,
Elongation in 3 ins., 39·1 per cent.
Contraction of area, 62·3 ,,



No. 52.—Heated to 1,000° C. for 15 minutes and cooled in ashes; showing increased size of Ferrite grains.

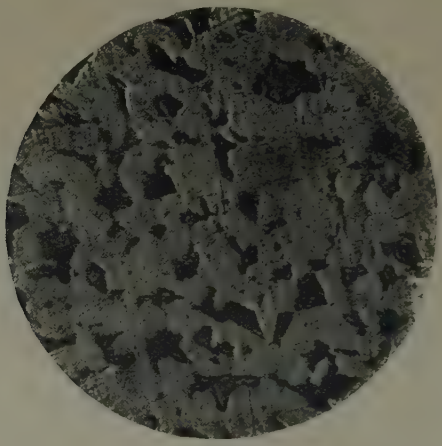
Tensile stress, . . 28·1 tons per square inch.
Elastic limit, . .. 14·2 ,, ,,
Elongation in 3 ins., 35·7 per cent.
Reduction of area, . 56·3 ,,



No. 53.—Heated to 1,160° C. for 5 minutes and cooled in ashes. Ferrite grains considerably increased in size.

Tensile stress, . . 27·3 tons per square inch.
Elastic limit, . . 14·1 ,, ,,
Elongation in 3 ins., 33·8 per cent.
Reduction of area, . 53·1 ,,

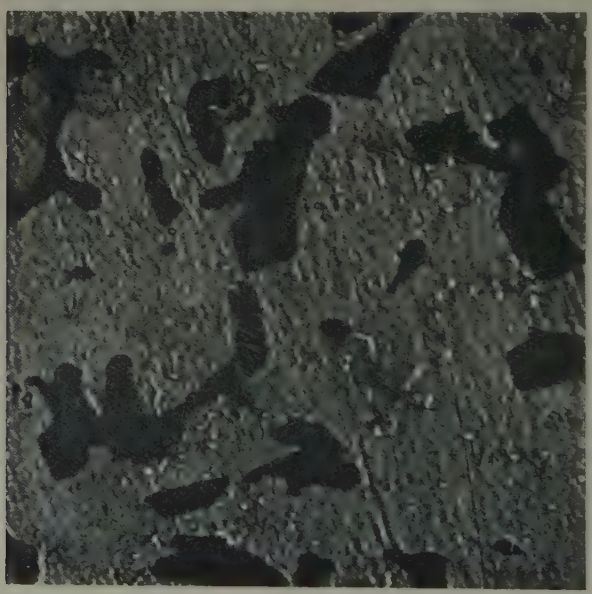
Although the differences in the mechanical properties are not greatly affected, it will be noticed that heating to 1,000° C. reduces both the tensile stress and elastic limit, and elongation, and this is more marked at 1,160° C. Had the heat treatment been prolonged for an hour instead of only being maintained for a few minutes, it is probable that these results would have been much more marked. Heating to 750°, or at all events to 820°, seems to give the best results and to insure the highest elastic limit combined with greatest elongation, and prolonging the heating does not seem to appreciably effect the mechanical properties, as shown in No. 51. The above illustrations, from a paper by Mr. Campion, were reproduced from blocks kindly lent by the Council of the West of Scotland Iron and Steel Institute.



No. 54.—Bar as rolled 1½ inches diameter. Magnification 150 diameters.

Carbon,	0·180	Maximum stress,	29·8 tons per square inch.
Silicon,	0·055	Elastic limit,	15·4 ,, ,,
Sulphur,	0·055	Elongation in 3 inches,	33·3 per cent.
Phosphorus,	0·071	Reduction of area,	57·6 ,,
Manganese,	0·560		

Bent over through 180° over radius of 2 inches without fracture.



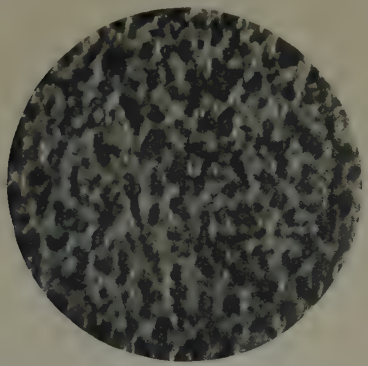
No. 55.—Same bar after heating for 36 hours packed in lime at a temperature of about 1,000° C., and cooling slowly for 32 hours. Magnification 150 diameters.

Maximum stress,	27·2 tons per square inch.	Elongation in 3 inches,	36·0 per cent
Elastic limit,	14·2 ,, ,,	Reduction of area,	57·6 ,,

Brittle under shock. Broke under two or three blows with a hammer.

Important to note that, although results in tensile machine excellent, material was brittle under sudden shock.

Carbon,	0·190
Silicon,	0·070
Sulphur,	0·044
Phosphorus,	0·053
Manganese,	0·453



No. 56.—Bar as rolled 1½ inches diameter bent through 180° over 2 inches radius. Magnification 150 diameters.

No. 57.—Same bar magnified 150 diameters, after removal from box of Siemens furnace slag, into which it had been dropped when the slag was molten and allowed to remain until the slag was cold.

So brittle that it broke with first blow of hammer.

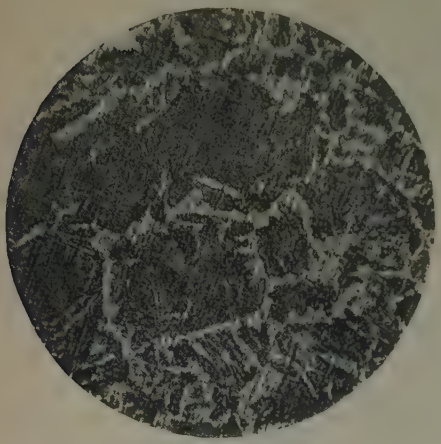
Photo-Micrographs from Oil Tempered Steel Axle 7 inches Diameter. Magnification 150 Diameters.

A section was taken across the diameter of the axle, and one piece was cut from outside, one piece 2 inches from outside, and one from centre.

It will be noticed that Ferrite grains are much larger in the sample from the centre, and in the outside sample the Ferrite is broken up and more diffused through the Pearlite areas. Under higher powers the outside sample is shown to contain a lot of unsegregated Pearlite, or Sorbite, while the Pearlite is more or less laminated in the sample from the centre.

Analysis.

Carbon,	0·35	Tensile strength,	37·2 tons per square inch.
Sulphur,	0·031	Elastic limit,	24·6 ,, ,,
Phosphorus,	0·038	Elongation in 3 inches,	28 per cent.
Manganese,	0·660	Reduction in area,	49·8 ,,

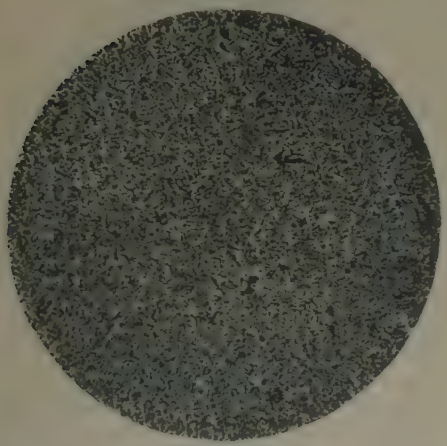


No. 58.—Sample from the outside.

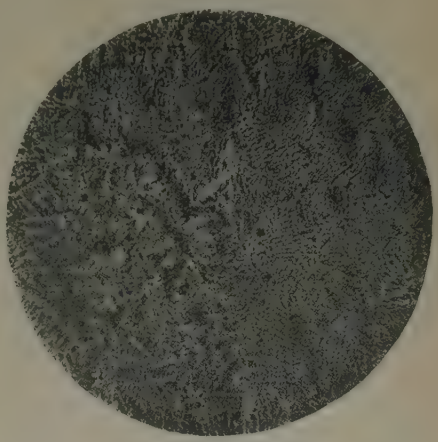
No. 59.—Sample taken 2 inches from outside.

No. 60.—Sample from the centre.

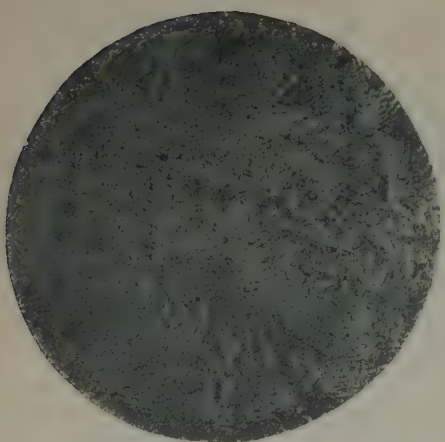
PHOTO-MICROGRAPHS SHOWING EFFECT OF FINISHING TEMPERATURE AND HEAVY AND LIGHT FORGING RESPECTIVELY ON SIZE OF GRAIN. MAGNIFICATION 50 DIAMETERS.



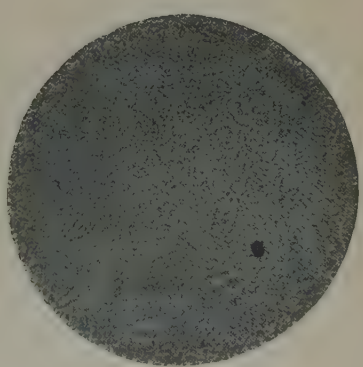
No. 61.—2-inch billet forged to ¾ inch square, finished at dull red heat.



No. 62.—Piece same billet, No. 61, forged to same size finished just below a yellow heat.



No. 63.—Same billet forged to 1 inch square by a *small* number of heavy blows, finished just below yellow heat.



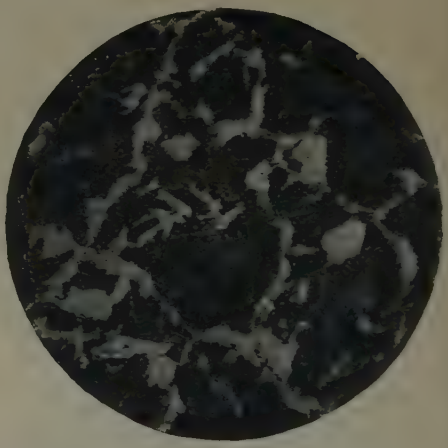
No. 64.—Same billet forged down to 1 inch square by a *large* number of light blows.

Photo-Micrographs of Two Rails and Cement Bar.

No. 65.—Steel rail as rolled. Interior of heads. Transverse section. Magnification 150 diameters.

Carbon,	0·363
Silicon,	0·042
Sulphur,	0·044
Phosphorus,	0·055
Manganese,	0·295

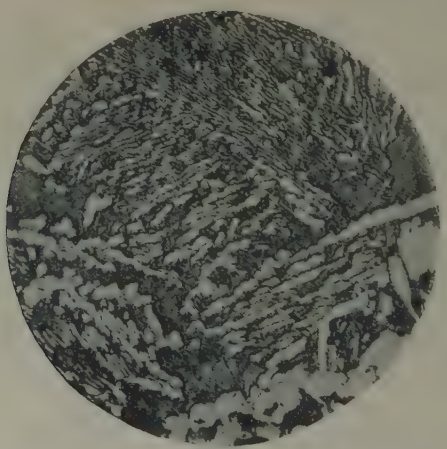
Example of low Carbon and low Manganese steel rail.



No. 66.—Steel rail as rolled. Transverse section. Magnification 150 diameters.

Carbon,	0·489
Silicon,	0·084
Sulphur,	0·050
Phosphorus,	0·069
Manganese,	0·970

Fairly high Carbon and high Manganese rail.



No 67.—Cement bar. Showing Pearlite and Cementite. Magnification 150 diameters.

APPENDIX I.

SPECIFICATIONS.

American Specifications.

Since the publication of the first edition of this work, comparatively few alterations have been made in the American Standard Specifications. The general tendency has been to insist upon lower Phosphorus in the rail specifications, and a Special Committee, appointed by the American Society of Civil Engineers to report on rail sections, recommended in their preliminary report of January, 1906, that the Phosphorus should not exceed ·085 per cent., and that the maximum Carbon percentage should be raised from 0·5 to 0·6 for 70- to 79-lb. rails, from 0·53 to 0·63 for 80- to 89-lb. rails, and from 0·55 to 0·65 for 90- to 100-lb. rails. The Committee were not quite unanimous in these recommendations, as the ·085 per cent. Phosphorus limit would rule out a large number of Bessemer acid works using pig iron produced from native ores, and the matter is under further consideration. Basic open hearth rails are now being used in the States, and the specification for this material permits of higher Carbon than in acid steel, at the same time reducing the Phosphorus limit to ·04 per cent. It has been recognised by American engineers that, for the same chemical composition, steel produced in the basic open hearth is softer than acid Bessemer steel, and it is quite safe to take higher Carbons, especially if, at the same time, a lower percentage of Phosphorus is insisted upon. This question of the influence of manufacture in relation to chemical composition on the physical properties of steel is an important one, which will probably have to receive more attention in the future than it has done in the past.

American Standard Specifications, Test Pieces, and Methods of Testing Iron and Steel, adopted by Committee No. 1 of the American Section of the International Association for Testing Materials.

The Committee recommends the following as the general requirements which international specifications should include :—

Process of Manufacture.—The process or processes of manufacture of a steel for a given purpose should be specified, but the details of the process should be left to the manufacturer, as a satisfactory product is produced by methods of manufacture varying in different countries.

The proportions of certain of the chemical constituents, especially Sulphur and Phosphorus, should be specified to be within certain limits, and limits should be prescribed to all physical properties which determine the suitability of the steel for the purpose intended.

The number and location of the test pieces should also be specified, the general methods of determining the physical properties specified given, and how the sample for chemical analysis should be taken.

The specifications should also contain clauses governing the required finish and branding of the material, and a clause granting the inspector the necessary facilities to see that the provisions of the specification are carried out.

For steel rails, the following clause may be inserted :—

"The entire process of manufacture and testing shall be in accordance with the best current practice, special care being given to the following instructions :—Ingots shall be kept in a vertical position in pit heating furnaces; no bled ingots shall be used; sufficient material shall be discarded from the top of the ingot to insure sound rails."

Chemical Requirements.—The general recommendations of the Committee as regards chemical composition are embodied in the tabulated specifications, but it is recommended that when the tensile strength is specified the Carbon shall be omitted, as a number of cases have occurred where the tensile strength specified could not be obtained by keeping the Carbon, and in some cases Manganese and Silicon, within the required limits.

It is considered that the chemical composition of the steel, other than limiting the amount of Phosphorus and Sulphur, may be left to the manufacturer if the physical properties required are properly specified.

Tensile Strength.—Tensile strength, which, except in the case of steel rails, is always required, is specified in order to insure the necessary strength in the material.

Yield Point and Elastic Limit.—The elastic limit is considered very important as being the true index of the resistance to working stress, but as it is not practicable in rapid commercial work to accurately determine this, the yield point is required with the tensile strength in all cases, with the exception of rails.

Elongation.—It is recommended that for structural steels, boiler plate and rivet steel, and splice bars the percentage of elongation be measured in 8 inches, and for castings, axles, forgings, and tires in 2 inches.

Contraction of Area.—This test is recommended for castings, axles, and forgings where the tensile strength is determined on a turned test specimen. A turned test specimen is also used for tires, but here the test is considered unnecessary for the high Carbon steel used, as the tires are very seldom annealed.

This test is a valuable one as an indication of the physical state and uniformity of the steel. Steel of good quality, which has received proper treatment as regards heating and mechanical work, always gives a good contraction of area in proportion to its tensile strength.

Bending Tests.—The cold bending tests are to be made on untreated bending specimens cut from the finished material.

The cold bending test, like contraction of area, indicates the physical condition of the metal. Steel capable of severe cold bending always shows high contraction of area and *vice versâ*.

Drop Tests.—These are recommended for axles, tires, and rails.

An axle must stand a certain number of blows from specified heights without rupture, the first blow to give a certain deflection which should not subsequently be exceeded.

A tire must stand, without breaking or cracking, successive blows from increasing heights until it shows a minimum deflection equal to $D^2 \div (40T^2 + 2D)$, where D is the internal diameter of the tire, and T the thickness at centre of tread.

A rail must not break or crack from a single blow from heights varying with the section of the rail.

It is considered that materials which will be subjected to shocks when in actual use should be tested by impact.

The Test Pieces and Methods of Testing Specified.—For steel castings, axles, forgings, and tires a standard turned test specimen is recommended $\frac{1}{2}$ inch diameter and 2 inches gauged length.

Tensile Specimens.—For the sheared plates used in structural steel for buildings, structural steel for bridges and ships, and in open hearth plate steel a standard test specimen 18 inches long, $1\frac{1}{2}$ inches wide, the thickness of the plate, of 8 inches gauged length is recommended. The parallel portion should not be less than 9 inches.

Methods for Tensile Tests.—When the yield point is required it may be determined by the careful observation of the drop of the beam or halt in the gauge of the testing machine.

The following are the dimensions of TEST SPECIMENS recommended:—

Bending Test.—For castings and forgings 1 inch wide by $\frac{1}{2}$ inch thick.

With structural steel for buildings, and for bridges and ships, and with open hearth plate and rivet steel, the width should be $1\frac{1}{2}$ inches if possible, and if the thickness of material is $\frac{3}{4}$ inch or less, the specimen should have the natural rolled surface on two opposite sides, but with material more than $\frac{3}{4}$ inch thick the specimen may be $\frac{1}{2}$ inch thick.

Methods for Bending Tests.—The bending test may be made by pressure or by blows.

Methods for Drop Test.—The following details are recommended:—

(*a*) *Rails.*—Pieces tested should not be more than 6 feet long. They should be placed head upwards on solid supports 3 feet apart. The anvil block should weigh at least 20,000 lbs., and the supports should be a part of, or firmly secured to, the anvil. The tup should weigh 2,000 lbs., and the striking face should have a radius of not more than 5 inches.

(*b*) *Tires.*—These should be placed vertically under the drop, in a running position, on a solid foundation of at least 10 gross tons in weight, and subjected to successive blows from a tup (2,240 lbs.) falling from increasing heights until the required deflection is obtained.

(*c*) *Axles.*—Axles should be placed on supports 3 feet apart, in such a position that the top will strike the axle midway between the ends.

Weight of anvil, ...	17,500 lbs.
Weight of tup, ...	1,640 lbs.
Radius of supports and striking face of tup in direction of the axis of the axle, . .	5 inches.

The anvil should be free to move in a vertical direction, and is supported by twelve helical springs on a cast-iron base, in turn resting on a solid foundation. The free height of the spring is $9\frac{1}{8}$ inches, and height under load of 6,650 lbs. 7 inches.

The following is a summary of the principal points recommended by the Committee for American specifications, and appended are specifications in tabulated form, showing the detailed tests, both chemical and mechanical, for different classes of material:—

AMERICAN STANDARD SPECIFICATIONS.

Axles, . . .	Process of manufacture, percentage of **P, S,** and **Ni,** tensile strength, yield point, elongation, contraction of area, drop test.
Tires, . . .	Process of manufacture, percentage of **Mn, Si, P, S,** tensile strength, elongation, drop test.
Castings, . .	Process of manufacture, percentage of **P** and **S,** tensile strength, yield point, elongation, contraction of area, drop test, percussive test, bending test.
Forgings, . .	Process of manufacture, percentage of **P, S, Ni,** tensile strength, yield point, elongation, contraction of area, bending test.
Rails, . . .	Process of manufacture, percentage of **C, Si, P, Mn,** drop test.
Structural Steel—Bridges & Ships,	Process of manufacture, percentage of **P** and **S,** tensile strength, yield point, elongation, bending tests.
Structural Steel—Buildings, . .	Process of manufacture, percentage of **P,** tensile strength, yield point, elongation.
Boiler Plate and Rivet Steel, .	Process of manufacture, percentage of **P, S,** and **Mn,** tensile strength, yield point, elongation.
Splice Bars, . .	Process of manufacture, percentage of **C, P,** and **Mn,** tensile strength, yield point, elongation, bending test.

	Process of Manufacture.	Percentage of Elements Specified.	Tensile Strength.	Yield Point.	Elongation.	Contraction of Area.	Drop Test.					
							Weight.	Distance between Supports.	Diameter Axle at Centre.	No. of Blows.	Drop in Feet.	Deflection in Inches.
Axles,	Open Hearth.	P, max. ·06 S, ,, ·06	Lbs. per sq. in. 80,000	40,000	18 % in 2″	.	Lbs. 1640	Feet. 3	Inches. .. 4½	.. 5	.. 24	.. 8¼
Ni Steel,		P, ,, ·04 S, ,, ·04 Ni, ,, 3·75	80,000	50,000	25 % in 2″	45 %	Weight of Anvil is 17,500 lbs. Axle must be turned over after first and third blow.		4⅝ 4 1 7/16 4⅝ 4¾ 5⅛ 5⅞	5 5 5 5 5 7	26 28½ 31 34 43 43	8¼ 8¼ 8 8 7 5½
							Without rupture and without exceeding, as result of first blow, deflection given.					
Tires.	Open Hearth or Crucible.	Mn, max. ·80 Si, min. ·20 P, max. ·05 S, ,, ·05	100,000 110,000	{Passenger engine} {Goods engine}	12 % in 2″ 10 % in 2″	.. ..	Lbs. 2240		Tire in running position—blows from increasing heights until deflection. $D^2 \div (40\,T^2 + 2D)$ Where D = int. diam. T = thickness at centre of tread.			
Castings,	Open Hearth, Crucible, or Bessemer, annealed or unannealed.	P, max. ·05 S, ,, ·05	85,000 70,000 60,000 27,000	38,250 31,500 27,000	15 % in 2″ 18 % in 2″ 22 % in 2″	20 % hard. 25 % medium. 30 % soft.	For small or unimportant castings—in place of tensile test—test to destruction.		Bending Test. — Test piece 1″ × ½″, bent cold round curve 1″ diam. without fracture— 120° for soft castings. 90° for medium castings. Percussive Test.—Castings to be suspended and hammered all over.			
Forgings— Soft Steel,	Open-Hearth, Crucible, or Bessemer.	S, max. ·10 P, max. ·10	58,000	29,000	28 % in 2″	35 %			Bending Test. — Test piece 1″ × ½″, shall bend cold 180° without fracture— For soft steel—round diam. ½″			
Carbon Steel not annealed,	..	·06 ·06	75,000	37,500	18 % in 2″	30 %			For carbon steel—not annealed, ,, 1½″			
Carbon Steel annealed,	..	·04 ·04	80,000	40,000 Elastic limit.	22 % in 2″	35 %			For carbon steel—from forging over 20″ dia., ,, 1½″ For annealed—from forging under 20″ dia., ,, 1″			

British Standard Specifications.

By the kind permission of the Engineering Standards Committee, I am permitted to give particulars of the principal British Standard Specifications so far as they relate to railway and structural materials. It will be seen that, with regard to chemical composition generally, they have followed the American practice in usually omitting to specify any percentage of Carbon when a tensile test is required, leaving the percentage of constituents other than Phosphorus and Sulphur to the manufacturer. In some cases limits for Silicon and Manganese are specified, and, generally, the process of manufacture is stated. The usual tensile tests, with elongation, are required, and in some cases cold bending tests, both on the untreated and quenched material, are specified.

Drop Tests.—These are required for rails, axles, and tires.

Rails.—The drop test for these varies with the section and weight of the rails. For flat-bottom rails pieces 5 feet in length are placed on bearings 3 feet apart, and for 70 lbs. to 100 lbs. on bearings 3 feet 6 inches apart. For bull heads, 5 feet lengths are taken, and bearings are 3 feet 6 inches apart. The striking face of the tup in each case must be rounded to a radius of not more than 5 inches. The following tables give details of tests for different rails :—

Flat Bottom Rails.

No. of "B.S." Section and Nominal Weight of Rail per Yard in Lbs.	Falling Weight Test.		
	Weight of Tup.	Centres of Bearings.	Drop.
	Cwts.	Feet.	Feet.
20,	5	3	8
25,	5	3	9
30,	10	3	10
35,	10	3	12½
40,	10	3	15
45,	15	3	15
50,	15	3	15
55,	15	3	17½
60,	20	3	20
65,	20	3	20
70,	20	3½	20
75,	20	3½	20
80,	20	3½	22
85,	20	3½	24
90,	20	3½	26
95,	20	3½	28
100,	20	3½	30

Bull Head Rails.

No. of "B.S." Section and Nominal Weight of Rails per Yards in Lbs.	Falling Weight of Test.					
	First Blow.			Second Blow.		
	Drop.	Deflection		Drop.	Deflection	
		From	To		From	To
	Feet.	Inch.	Inches.	Feet.	Inches.	Inches.
60,	5	1	$1\frac{5}{16}$	10	3	$3\frac{3}{4}$
65,	5	1	$1\frac{1}{4}$	12	3	$3\frac{3}{4}$
70,	6	1	$1\frac{5}{16}$	12	3	$3\frac{3}{4}$
75,	6	1	$1\frac{5}{16}$	12	3	$3\frac{3}{4}$
80,	6	$\frac{7}{8}$	$1\frac{3}{16}$	15	3	4
85,	6	$\frac{7}{8}$	$1\frac{3}{16}$	15	3	4
90,	7	$\frac{7}{8}$	$1\frac{1}{4}$	20	3	$4\frac{1}{4}$
95,	7	$\frac{7}{8}$	$1\frac{5}{16}$	20	3	$4\frac{1}{4}$
100,	7	$\frac{7}{8}$	$1\frac{3}{16}$	20	3	$4\frac{1}{4}$

Axles.—Locomotive straight axles have to be placed upon bearings resting on a block of metal of not less than 5 tons weight, supported on a rigid concrete or other solid foundation, and must withstand, without fracture, five blows from a falling weight of 2,240 lbs. as specified below.

The axle is to be turned after the first and third blow, and is to be broken after testing, both in the centre and at the journals.

Diameter of Axle at Centre.	Number of Blows.	Height of Fall, in Feet.	Distance Apart of Bearings.	
			Ft.	Ins.
Under 4 inches,	5	16	3	0
4 inches and under $4\frac{1}{4}$ inches,	5	18	3	6
$4\frac{1}{4}$,, ,, $4\frac{1}{2}$,,	5	20	3	6
$4\frac{1}{2}$,, ,, $4\frac{3}{4}$,,	5	22	3	6
$4\frac{3}{4}$,, ,, 5 ,,	5	24	3	6
5 ,, ,, $5\frac{1}{4}$,,	5	24	4	0
$5\frac{1}{4}$,, ,, $5\frac{1}{2}$,,	5	28	4	0
$5\frac{1}{2}$,, ,, $5\frac{3}{4}$,,	5	28	4	6
$5\frac{3}{4}$,, ,, 6 ,,	5	32	4	6
6 ,, and over,	5	35	5	0

In the case of carriage and waggon axles, the following drop tests are specified, the bearings resting on a solid foundation, as in the case of locomotive axles :—

Diameter of Axle at Centre.	Number of Blows.	Height of Fall, in Feet.	Distance Apart of Bearings.
			Ft. Ins.
Under 3¾ inches, ...	5	15	3 0
3¾ inches and under 4 inches, . . .	5	16	3 0
4 ,, ,, 4¼ ,, . . .	5	18	3 6
4¼ ,, ,, 4½ ,, . . .	5	20	3 6
4½ ,, ,, 4¾ ,, . . .	5	20	3 6
4¾ ,, ,, 5 ,, . . .	5	24	3 6
5 ,, ,, 5¼ ,, . . .	5	24	4 0
5¼ ,, ,, 5½ ,, . . .	5	28	4 0
5½ ,, ,, 5¾ ,, . . .	5	28	4 6
5¾ ,, ,, 6 ,, . . .	5	32	4 6
6 ,, and over, ...	5	35	5 0

Tires.—A locomotive tire has to stand the following test:—The tire is to be placed in a running position, with the tread resting on a block of metal of not less than 5 tons in weight, supported on a rigid concrete foundation, and must withstand, without fracture, blows from a falling weight of 2,240 lbs. The weight is to be allowed to fall freely from heights of 10, 15, and 20 feet and upwards, until the deflection of the tire corresponds to that given in the following table :—

Internal Diameter of Tire. d.	Class B. Tensile Breaking Strength, 42 to 48 tons per square inch.	Class C. Tensile Breaking Strength, 50 to 55 tons per square inch.	Class D. Tensile Breaking Strength, 56 to 62 tons per square inch.
3 feet and over, . . .	$\frac{1}{8}$ d.	$\frac{1}{8}$ d.	$\frac{1}{10}$ d.
Under 3 feet, . . .	$\frac{1}{8}$ d.	$\frac{1}{10}$ d.	$\frac{1}{12}$ d.

The tests for carriage and waggon tires are the same as regards the falling weight and height, until the following deflections are shown :—

Internal Diameter of Tire. d.	Class B. Tensile Breaking Strength, 42 to 48 tons per square inch.	Class C. Tensile Breaking Strength, 50 to 55 tons per square inch.	Class D. Tensile Breaking Strength, 56 to 62 tons per square inch.
3 feet and over, . . .	$\frac{1}{8}$ d.	$\frac{1}{8}$ d.	$\frac{1}{10}$ d.
Under 3 feet, . . .	$\frac{1}{8}$ d.	$\frac{1}{10}$ d.	$\frac{1}{12}$ d.

The following tables give a summary of various British Standard Specifications, but full particulars as to detailed requirements are obtainable only from the following publications of the Engineering Standards Committee, which can be obtained at their offices, 28 Victoria Street, Westminster, S.W. :—

No. 2. *Tramway Rails and Fishplates.*
„ 9. (Revised July, 1909) *Bull-head Railway Rails.*
„ 11. (Revised July, 1909) *Flat-bottom Railway Rails.*
„ 13. (Revised July, 1906) *Structural Steel for Shipbuilding.*
„ 14. (Revised March, 1907) *Structural Steel for Marine Boilers.*
„ 15. *Structural Steel for Bridges and General Building Construction.*
„ 24. (Revised June, 1907) *Railway Rolling Stock Materials.*

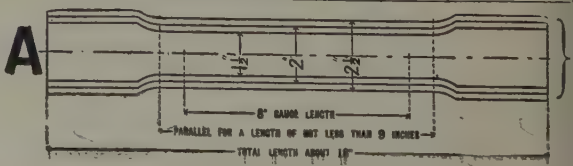
THE ENGINEERING

COMPARISON OF

LINE.		MATERIAL.	TENSILE TESTS. Tensile Breaking Strength. Tons per Square Inch.	Minimum Extension per cent. on Standard Test Piece.	Standard Test Piece.	Limit of Elasticity per cent. of Ult. Tensile Strength.	Number of Tests.
1	STEEL PLATES.	For Locomotive Frames, .	28-32	20 for ·375″ & above, 16 below ·375″.	A	—	2 each cast, . . .
2		,, Do., .	28-32	Do.	A	—	Do., . . .
3		,, Carriage and Waggon Underframes,	28-32	20 for ·312″ & above, below ·312″, no test.	A	—	1 each cast or 25 tons, (*a*)
4		,, Do. do.,	28-32	Do.	A	—	Do.,
5		,, Bridges, ...	28-32	Do.	A	—	Do.,
6		,, General Building Construction,	28-32	Do.	A	—	Do.,
7		,, Ships, ...	28-32	20 for ·375″ & above, 16 below ·375″.	A	—	1 each charge; 2 if charge exceeds 25 tons,
8		,, Locomotive Boilers, .	26-32	22 all thicknesses.	A	—	1 each end of each plate as rolled,
9		,, Marine Boilers, . .	28-32	20 for ·375″ & above, 17 below ·375″.	A	—	1 each plate; plates over 2½ tons, 1 each end,
10		,, Marine Boilers (for flanging),	26-30	23 for ·375″ & above, 20 below ·375″.	A	—	Do.,
11		,, Ships (for cold flanging),	26-32	20 for ·375″ & above, 16 below ·375″.	A	—	1 each charge; 2 if charge exceeds 25 tons,
12	STEEL SECTIONAL MATERIAL AND BARS (Other than Rivet Bars).	For Locomotive Frames, .	28-32	20 for ·312″ & above, below ·312″, no test.	A or B	—	2 each cast, . . .
13		,, Do., .	28-32	Do.	A or B	—	Do., . . .
14		,, Carriage and Waggon Underframes,	28-32	Do.	A or B	—	1 each cast or 25 tons, (*a*)
15		,, Do. do.,	28-32	Do.	A or B	—	Do.,
16		,, Bridges, . . .	28-32	Do.	A or B	—	Do.,
17		,, General Building Construction,	28-32	Do.	A or B	—	Do.,
18		,, Ships, ...	28-33	20 for ·375″ & above, 16 below ·375″.	A or B	—	1 each charge; 2 if charge exceeds 25 tons,
19		,, Locomotive Boilers, .	26-32	22 all thicknesses.	A or B	—	2 each cast, . . .
20		,, Marine Boilers (Stay, Angle, and T Bars),	28-32	20 for ·375″ & above, 17 below ·375″.	A or B	—	2 each charge, . (*b*)
21		,, Do. (Combustion Chamber Stays),	26-30	23 for ·375″ & above, 20 below ·375″.	B	—	Do., . (*b*)

(*a*) Whichever is least.

(*b*) When number of bars from one charge exceeds 15, one additional test for each further 15 or portion thereof.



STANDARDS COMMITTEE. *August, 1910.*

TESTING REQUIREMENTS.

8	9	10	11	12	13	14	15	16
BEND TESTS.					PERCENTAGE OF IMPURITIES.			
Size of Test Piece.	Internal Radius of Bend.	Angle of Test, in Degrees.	Number of Tests	PROCESS OF MANUFACTURE.	Phosphorus.	Sulphur.	Silicon.	LINE.
Not less than 1·5″ wide,	Not greater than 1·5 times thickness,	180	1 cold or 1 temper from each plate as rolled,	Open hearth, Acid or Basic,	·06	·06	—	1
Do.,	Do.,	180	Do.,	Do.,	Not required.		—	2
Do.,	Do.,	180	2 per cent. cold and 2 per cent. temper,	Do.,	·06	·06	—	3
Do.,	Do.,	180	Do.,	Do.,	Not required.		—	4
Do.,	Do.,	180	1 cold or 1 temper from each plate as rolled.	Do.,	·06	·06	—	5
Do.,	Do.,	180	Do.,	Do.,	·06	·06	—	6
Do.,	Equal to 1·5 times thickness,	180	Do.,	Do.,	Not required.		—	7
Do.,	Not greater than thickness,	180	Do.,	Open hearth, Acid,	·05	·05	—	8
Do.,	Equal to 1·5 times thickness,	180	Do., (c)	Open hearth, Acid or Basic,	Not required.		—	9
Do.,	Do.,	180	Do., (c)	Do.,	Do.		—	10
Do.,	Do.,	180	1 cold from each plate,	Do.,	Do.		—	11
Not less than 1·5″ wide,	Not greater than 1·5 times thickness,	180	1 cold or 1 temper from each section or bar as rolled,	Open hearth, Acid or Basic,	·06	·06	—	12
Do.,	Do.,	180	Do.,	Do.,	Not required.		—	13
Do.,	Do.,	180	2 per cent. cold and 2 per cent. temper,	Do.,	·06	·06	—	14
Do.,	Do.,	180	Do.,	Do.,	Not required.		—	15
Do.,	Do.,	180	1 cold or 1 temper from each section or bar as rolled,	Do.,	·06	·06		16
Do.,	Do.,	180	Do.,	Open hearth or Bessemer, Acid or Basic,	·07	·06	—	17
Do.,	Equal to 1·5 times thickness,	180	Do.,	Open hearth, Acid or Basic,	Not required.		—	18
Do.,	Not greater than thickness,	180	Do.,	Open hearth, Acid,	·05	·05	—	19
Do.,	Equal to 1·5 times thickness,	180	Do.,	Open hearth, Acid or Basic,	Not required.		—	20
Do.,	Do.,	180	1 cold and 1 temper from every 15 bars as rolled from each charge,	Do.,	Do.		—	21

{ Maximum width for thicknesses over $\frac{3}{4}$ inch, . $1\frac{1}{2}$ inches.
{ ,, ,, ,, from $\frac{5}{8}$ to $\frac{7}{8}$ inch, 2 ,,
{ ,, ,, ,, less than $\frac{5}{8}$ inch, $2\frac{1}{2}$,,

(*See Figure* A *opposite.*)

(c) Plates over $2\frac{1}{2}$ tons. one cold and one temper, from each end.

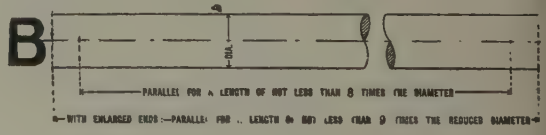
COMPARISON OF

1	2	3	4	5	6	7
		TENSILE TESTS.				
LINE.	MATERIAL.	Tensile Breaking Strength. Tons per Square Inch.	Minimum Extension per cent. on Standard Test Piece.	Standard Test Piece.	Limit of Elasticity per cent. of Ult. Tensile Strength.	Number of Tests.
22	STEEL RIVET BARS. For Locomotive Frames, .	26-30	25	B	—	2 each cast, . . .
23	,, Do., .	26-30	25	B	—	Do., . . .
24	,, Carriage and Waggon Underframes,	26-30	25	B	—	1 each cast or 25 tons, (*a*)
25	,, Do. do.,	26-30	25	B	—	Do.,
26	,, Bridges, ...	26-30	25	B	—	Do.,
27	,, General Building Construction,	26-30	25	B	—	Do.,
28	,, Ships, ...	25-30	25	B	—	1 each charge, . (*d*)
29	,, Locomotive Boilers, .	26-30	25	B	—	2 each cast, . . .
30	,, Marine Boilers, . .	26-30	25	B	—	2 each charge, . (*b*)
31	STEEL RAILS. For Bull-head (railway),	40-48	15	C or D	—	1 each 100 tons, . .
32	,, Flat-bottom (railway),	40-48	15	C or D	—	Do., . .
33	,, Tramway, . . .	40 min.	10½	C or D	—	Do., . .
34	STEEL AXLES. For Locomotive Crank Axles,	30 min. 35 min. (oil hardened)	25 20	C or D	50	1 each web, . . (*f*)
35	,, Do.,	30 min. 35 min. (oil hardened)	25 20	C or D	50	Do., . . .
36	,, Loco. Straight Axles, .	35-40	25-20	C or D	50	2 per cent., but at least 1 each cast,
37	,, Do., .	35-40	25-20	C or D	50	Do.,
38	,, Carriage and Waggon Axles,	35-40	25-20	C or D	50	Do.,
39	,, Do.,	35-40	25-20	C or D	50	Do.,

(*a*) Whichever is least.

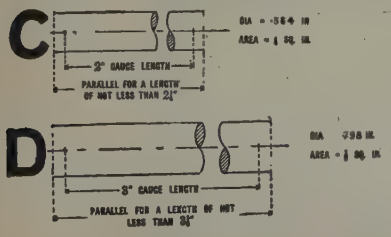
(*b*) When number of bars from one charge exceeds 15, one additional test for each further 15 or portion thereof.

(*d*) When weight of bars exceeds, from one charge, 10 tons, one additional test for each further 10 tons or portion thereof.


B
DIA.
PARALLEL FOR A LENGTH OF NOT LESS THAN 8 TIMES THE DIAMETER
WITH ENLARGED ENDS:—PARALLEL FOR A LENGTH OF NOT LESS THAN 9 TIMES THE REDUCED DIAMETER

TESTING REQUIREMENTS.—*Continued.*

8	9	10	11	12	13	14	15	16
BEND TESTS.					PERCENTAGE OF IMPURITIES.			
Size of Test Piece.	Internal Radius of Bend, in Inches.	Angle of Test, in Degrees.	Number of Tests.	PROCESS OF MANUFACTURE.	Phosphorus.	Sulphur.	Silicon.	LINE.
COLD BENDS.		HOT FLANGING TESTS.						
The rivet shank to be bent cold, as shown in sketch.		The rivet head to be flattened as shown in sketch until 2½ times the diameter of shank without crack at edges.		Open hearth, Acid or Basic,	·06	·06	—	22
				Do.,	Not required.		—	23
				Do.,	·06	·06	—	24
				Do.,	Not required.		—	25
				Do.,	·06	·06	—	26
				Do.,	·06	·06	—	27
				Do.,	Not required.		—	28
				Open hearth, Acid,	·05	·05	—	29
				Open hearth, Acid or Basic,	Not required.		—	30
No bend tests, but tup test as given on pp. 495 and 496.				Open hearth or Bessemer, (*e*) Acid or Basic, (*g*)	·075 Acid or Basic.	·08	·10	31
				(*e*) Do., (*h*)	·07 Acid or Basic.	·07	·10	32
				(*f*) Do., (*g*)	·08 Acid or Basic.	·08	·10	33
9″ long × 1·25″ square,	1·25	90, and ends brought together,	1 cold each web, (*j*)	Open hearth, Acid,	·035	·035	—	34
Do.,	1·25	Do.,	Do.,	Do.,	Not required.		—	35
Do.,	1·25	Do.,	2 per cent. cold, but at least 1 each cast, (*k*)	Do.,	·035	·035	—	36
Do.,	1·25	Do.,	Do., (*i*)	Do.,	Not required.		—	37
Do.,	1·25	Do.,	Do., (*i*)	Do.,	·035	·035	—	38
Do.,	1·25	Do.,	Do., (*i*)	Open hearth or Bessemer, Acid,	Not required.		—	39
All axles are required to stand a falling weight test, which varies with diameter of axle, see pp. 496 and 497.								


C
DIA = ·564 IN
AREA = ¼ SQ. IN.
2″ GAUGE LENGTH
PARALLEL FOR A LENGTH OF NOT LESS THAN 2½″
D
DIA ·798 IN.
AREA = ½ SQ. IN.
3″ GAUGE LENGTH
PARALLEL FOR A LENGTH OF NOT LESS THAN 3½″

(*e*) Also specified { Carbon, ·35 to ·50. Manganese, ·70 to 1·0.

(*f*) Also specified { Carbon, ·40 to ·55. Manganese, ·70 to 1·0.

(*g*) Carbon determinations of each cast required.

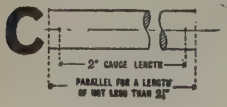
(*h*) Carbon and Phosphorus determinations of each cast required.

(*i*) Only for orders of 15 axles and under when drop test is not taken.

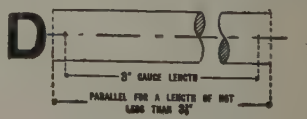
(*j*) For round webs, 1 each end of axle.

COMPARISON OF

Line	2 Material	3 Tensile Breaking Strength Tons per sq. Inch.	4 Minimum Extension per cent on Standard Test Piece.	5 Standard Test Piece.	6 Limit of Elasticity per cent of Ult. Tensile Strength.	7 Number of Tests.
		TENSILE TESTS.				
STEEL TIRES.						
40	For Loco. Tires, Class B,	42-48	18-15	C	—	2 per cent., but at least 1 each cast.
41	,, Do. do.,	42-48	18-15	C	—	Do.,
42	,, Do., Class C,	50-55	13-11	C	—	Do.,
43	,, Do. do.,	50-55	13-11	C	—	Do.,
44	,, Do., Class D,	56-62	10- 8	C	—	Do ,
45	,, Do. do.,	56-62	10- 8	C	—	Do.,
46	,, Carriage and Waggon Tires, Class A,	35-40	25-20	C	—	Do.,
47	,, Do., Class B,	42-48	18-15	C	—	Do ,
48	,, Do. do.,	42-48	18-15	C	—	Do.,
49	,, Do., Class C,	50-55	13-11	C	—	Do.,
50	,, Do., Class D,	56-62	10- 8	C	—	Do.,
STEEL FORGINGS.						
51	For Locos., Blooms, Class A, special, case-hardened,	Up to 27	25	C or D	—	1 each cast, . . .
52	,, Do., Forgings, do.,	Up to 27	25	C or D	—	2 per cent., but at least 1 each cast,
53	,, Do., Blooms, Class B, ordinary,	25-32	27-20	C or D	—	1 each cast, . . .
54	,, Do., Forgings, do.,	25-32	27-20	C or D	—	2 per cent., but at least 1 each cast,
55	,, Do., Blooms, Class C, special, without wearing surfaces.	32-37	25-20	C or D	50	1 each cast, . . .
56	,, Do., Forgings, do.,	32-37	25-20	C or D	50	2 per cent., but at least 1 each cast,
57	,, Do., Blooms, Class D, special, with wearing surfaces	40-45	20-15	C or D	50	1 each cast, . . .
58	,, Do., Forgings, do.,	40-45	20-15	C or D	50	2 per cent., but at east 1 each cast,
59	,, Marine work, . .	28-40 Not more than 4 tons between any max. and min. specified.	29-17 Quality factor, 57	C or D	—	At least 1 each forging,
STEEL CASTINGS.						
60	For Locos., General Castings,	35 min. (*k*) 26 min. (*l*)	10 (*k*) 15 (*l*)	C or D	—	1 each melting, . .
61	,, Do., Large or Important Castings,	35 min. (*k*) 26 min. (*l*)	10 (*k*) 15 (*l*)	C or D	—	Do , . .
62	,, Do., Wheel Centres, .	26 min.	15	C or D	—	Do., . .
63	,, Marine Work, Grade A, ,, Do. do., B, ,, Do. do., C, ,, Do. do., D,	35-40 26-35 26-35 —	15 20 15 —	C, D, or E	—	At least 1 each charge (*n*). if casting made from more than 1 charge, at least 4.



(*k*) For castings with wearing surfaces.
(*l*) For castings without wearing surfaces.
(*m*) For waggon wheel centres, 1 each melting,
(*n*) Small castings, at least 1 for each pouring head.



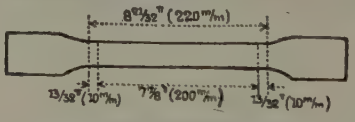
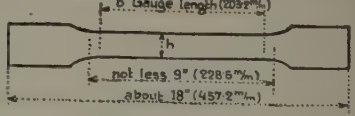
TESTING REQUIREMENTS.—*Continued.*

8	9	10	11	12	13	14	15	16
BEND TESTS.					PERCENTAGE OF IMPURITIES.			
Size of Test Piece.	Radius of Bend in Inches.	Angle of Test in Degrees.	Number of Tests	PROCESS OF MANUFACTURE.	Phosphorus	Sulphur	Silicon.	LINE.
—	—	—	—	Open hearth, Acid, . .	·035	·035	—	40
—	—	—	—	Do., . .	Not requi	red	—	41
—	—	—	—	Do., . .	·035	·035	—	42
—	—	—	—	Do., . .	Not requi	red	—	43
—	—	—	—	Do., . .	·035	·035	—	44
—	—	—	—	Do., . .	Not requi	red	—	45
—	—	—	—	Open hearth or Bessemer, Acid,	Do.		—	46
—	—	—	—	Open hearth, Acid, . .	·035	·035	—	47
—	—	—	—	Open hearth or Bessemer, Acid,	Not requi	red	—	48
—	—	—	—	Open hearth, Acid, . .	·035	·035	—	49
—	—	—	—	Do., . .	·035	·035	—	50
All tires are required to stand a falling weight test, which varies with the internal diameter of the tire, see pp. 497 and 498.								
9″ long×1·25″ square,	1·25	90 and ends brought together,	1 cold each cast, . .	Open hearth, Acid or Basic,	·05	·05	—	51
Do.,	1·25	Do.,	2 per cent. cold, but at least 1 each cast,	Do., . .	Not requi	red	—	52
Do.,	1·25	Do.,	1 cold each cast, . .	Do., . .	·06	·06	—	53
Do.,	1·25	Do.,	2 per cent. cold, but at least 1 each cast,	Do., . .	Not requi	red	—	54
Do.,	1·25	Do.,	1 cold each cast, . .	Open hearth, Acid, . .	·035	·035	—	55
Do.,	1·25	Do.,	2 per cent. cold, but at least 1 each cast,	Do., . .	Not requi	red	—	56
Do.,	1·25	Do.,	1 cold each cast, . .	Do., . .	·035	·035	—	57
Do.,	1·25	Do.,	2 per cent. cold, but at least 1 each cast,	Do., . .	Not requi	red	—	58
1″ wide × ·75″ thick,	Up to 32 tons max. tensile, ·25 in. Above 32 up to 36 tons max. tensile, ·375 in. Above 36 up to 40 tons max tensile, ·625 in.	180	At least 1 cold each forging,	Open hearth, Acid or Basic,	—	—	—	59
9″ long × 1″ diameter,	1·25	90	1 cold each melting, (*l*)	Open hearth or Bessemer, Acid or Basic,	·07	·07	—	60
Do.,	1·25	90	1 cold each casting, (*l*)	Do.,	·07	·07	—	61
Do.,	1·25	90	1 cold each wheel centre,	(*m*) Do.,	·07	·07	—	62
1″ wide × ·75″ thick,	1·0 1·0 1·0 —	60 120 90 —	At least 1 cold each charge (*m*), if casting made from more than 1 charge, at least 4,	Open hearth, Acid or Basic, Do., Do., Do.,	— — — —	— — — —	— — — —	63

All the tests given in the above tables are reconsidered by the Committee every year, and consequently are liable to be altered from time to time.

The International Association for Testing Materials have recently published a comparative summary of specifications for Great Britain, United States of America, and Germany, for structural steel, rails, and fish plates, based on Standard Specifications published in the respective countries by Engineering Standards Committee, the American Society for Testing Materials, and the Deutsche Verband für Materialprüfungen der Technik, and they are appended.

SPECIFICATIONS FOR

		Germany.	Great Britain.
1	Material	Siemens-Martin or Bessemer (Thomas).	Siemens-Martin: Plates, rivets, and sectional material for bridges; plates and rivets for general building construction. / Siemens-Martin or Bessemer: Sectional material for general building construction.
2	Finish	Smooth, free from cracks, blisters, and defective edges.	Free from cracks, surface flaws, laminations, &c.
3	Chemical Analysis and Certificate	....	Of each cast upon request of purchaser.
4	Chemical Composition	....	Bridges, per cent.: P, 0·06; S, 0·06. Building Construction, per cent.: P, 0·06 plates and rivets, 0·07 sectional material; S, 0·06.
5	Branding	Each piece to be marked, with No. of cast, in case of cast test being agreed upon.	All plates and sectional material marked in 2 places with maker's name or trademark, place where made, and No. or marks by which they can be traced to cast.
6	No. of Test Pieces	In case of a cast test being agreed upon: 3 pieces from each cast at most, however, 1 piece from every lot of 20 pieces or part thereof. In case of no cast test being agreed upon: 5 from each 100, at most, however, 1 piece from every 2 tons or part thereof.	One tensile test from every cast or 25 tons, whichever is least. One cold and one temper bend test from each plate, section, or bar, as rolled.
7	Shape of Test Specimens	Area = ½ – ¾ sq. in. (300-500 mm.²) for tensile strength. For rounds of less than diameter: $\frac{3}{12}$" (20 mm.): $l = 10\sqrt{}$ diameter:  For Bend Tests. Width $1\frac{1}{16}$ – $1\frac{3}{16}$ (30-50 mm.). Bar, rods, etc., in thickness according to use. Outer skin not to be damaged.	For Plates and other Structural Material. For thickness: > ½" (22·2 mm.); ⅜"-½" (9·5-22·2 mm.); < ⅜" (9·5 mm.). h = 1½" (38·1 mm.); 2" (50·8 mm.); 2½" (63·5 mm.).  For Bars, Rods and Stays. Parallel for length of not less than 8 times diameter. With enlarged ends: parallel for length of not less than 9 times reduced diameter. Rivet bars tested full size as rolled. Bend test pieces to be not less than 1½ in. (38·1 mm.) wide.
8	Test Pieces	Cold, sheared edges, etc., removed by milling, planing, etc. Test piece to be annealed only when material from which it is taken is to be annealed.	Test pieces to be cut lengthwise or crosswise from plates, and lengthwise from Sectional Material and Bars. When material is annealed or otherwise treated, test pieces to be similarly treated. Straightening to be done cold. Sheered edges to be removed by milling, planing, etc.

STRUCTURAL STEEL.

U. S. A.

Structural Steel for Bridges.	Structural Steel for Buildings.
Siemens-Martin.	Siemens-Martin or Bessemer.

Smooth, free from injurious seams, flaws, cracks, &c.

Certificate *re* contents of :

P, S, and Mn. | P.

Highest values in percentage.

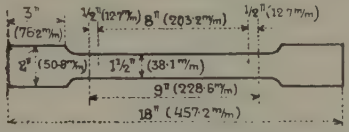
Structural Steel.		Rivet Steel.	Structural Steel.		Rivet Steel.
P.	Basic, - - - 0·04	0·04	Bessemer, - - - 0·1		
	Acid, - - - 0·06	0·04	Open hearth, - - 0·06		0·06
S.	- - - - 0·05	0·04			

Every finished piece of steel marked with blow No. and name of manufacturer, except that rivet and lattice steel and other small parts may be bundled with above marks on attached metal tag.

Every finished piece of steel stamped with blow No. except that small pieces may be shipped in bundles with metal tag attached.

At least 1 tensile test and 1 bending test from each melt of steel as rolled.

For tensile and bending tests for plates, shapes, and bars.



Milled to form shown in sketch, or with both edges parallel; or they may be turned to a diameter of ¾" (19·1 mm.) for a length of at least 9" (228·6 mm.), with enlarged ends.

The standard shape of the test specimen for sheared plates shall be as shown by the sketch. For other material the test specimen may be the same as for sheared plates, or it may be planed or turned parallel throughout its entire length, and, in all cases where possible, two opposite sides of the test specimen shall be the rolled surfaces.

Rivet rounds tested as rolled.

Special regulations for pins and rollers.

When material is annealed or otherwise similarly treated, test pieces to be similarly treated.

SPECIFICATIONS FOR

Germany.

9 Physical Tests, Properties

Only for a thickness of $\frac{3}{32}$"–$1\frac{3}{32}$" (7 to 28 mm.).
[For other thicknesses as to be agreed upon.]

A. Tensile Tests.

	Tensile Strength, lbs./sq. in.	Elongation per cent.
Lengthwise	52·625-62·581 (37-44 kg./mm.²)	≧ 20
Crosswise	51·203-64·004 (36-45 kg./mm.²)	≧ 17
Rivets and bolts	51·203-59·737 (36-42 kg./mm.²)	≧ 22

B. Other Tests.

1. Plate, Section or Bar.

(*a*) Bend Tests.

	Test piece lengthwise.	Test piece crosswise.
Heating, -	Light red hot	Light red hot.
Quenching,	Water 28° C.	Water 28° C.
Diameter of loops,	Single thickness.	Double thickness.
Fractures,	Not permissible.	Surface fractures permissible.

(*b*) Red Hot Breaking Tests.

Got off by forging.	Condition.	Punch.	Fracture
Area: $1\frac{9}{16} \times 1\frac{1}{2}$" (40×6 mm.)	Red hot.	$l = 3\frac{5}{32}$" (80 mm.) $d_1 = \frac{25}{32}$" (20 mm.) $d_2 = 1\frac{3}{16}$" (30 mm.)	Not permissible.

2. Rivet and Bolt Material.

(*a*) Bend Tests.

Section, - - Bars, rods, &c.
Heating, - - Light red hot.
Quenching, - Water at 28° C. (80° F.)
Diam. of loop, - Half thickness.
Fracture, - - Not permissible.

(*b*) Jumping Tests.

Length before jumping = 2 × diameter.
Heating, as by riveting.
Length after jumping = $\frac{3}{5}$ × diameter.

10 Rejection

For each test that fails, 2 further tests to be made from corresponding material, but should either of latter tests fail, material can be rejected
Should test piece break outside of the middle third of gauged length, another test to be made, if elongation insufficient.

11 Pemissible Variations

—

Great Britain.

	Tensile Strength, lbs./sq in.	Minimum Elongation per cent.
Plates and sectional material	62·720-71·680 (44·1-50·5 kg./mm.²)	20

For material under $\frac{7}{16}$ inch (7·9 mm.) thick, bend tests only are required.

Rivet bars	58·240-67·200 (41·0-47·3 kg /mm.²)	25

Bend test unnecessary for rivet bars.

Manufactured Rivets—Cold Bend Test.

The shank shall be bent 180° until 2 parts of shank touch, without fracture on outside of bend.
Rivet head will be flattened, white hot, until its diameter is 2½ times that of the shank, without cracking at edges.

Bend Tests—Cold and Hot.

When hot.

Heating, - - - Blood red.
Quenching, - - - 28° C. (80° F.)
Bending, - - - 180°

Test pieces to withstand, without fracture, being doubled over until internal radius not greater than 1½ times thickness of test piece, and the sides are parallel.

Should test pieces first selected not fulfil requirements, 2 further tests may be made, but should either fail, material from which test pieces were cut shall be rejected.
Further tests to be made before material from same cast is accepted.
Should a tensile test piece break outside middle half of its gauge length, test may be discarded and another test made from same material.

± 2½% calculated weight.

STRUCTURAL STEEL.

U. S. A.

Structural Steel for Bridges.

	Tensile Strength, lbs./sq. in.	Elongation. l	Elongation. 1,500,000 / Tensile Strength, per cent.
Structural Steel	60,000 (42·2 kg./mm.²)	8 ins. (203·2)	≧ 23
Rivet Steel	50,000 (35·2 kg./mm.²)	8 ins. (203·2)	≧ 27

Character of fracture—Silky.

Elongation—For material less than $\frac{5}{16}$″ (7·9 mm.) and more than $\frac{3}{4}$″ (19·1 mm.) in thickness, following modifications allowed.

(*a*) For each $\frac{1}{16}$″ (1·6 mm.) in thickness below $\frac{5}{16}$″ (7·9 mm.), a deduction of 2½ per cent.
(*b*) For each $\frac{1}{16}$″ (1·6 mm.) in thickness above $\frac{3}{4}$″ (19·1 mm.), a deduction of 1 per cent.

Special regulations for pins.

Bend Tests, by Pressure or Blows.

Plates, shapes, and bars up to 1″ (25·4 mm.) thick; cold bend, without fracture, to 180°.

Eye-bars and other steel 1″ (25·4 mm.) thick and over, tested as rolled.

Cold Bend.	Diameter of Loop.	Without fracture on outside of bend.
180°	Double thickness.	

Angles under Hammer.

$\frac{1}{2}$″ (12·7 mm.) and less thick bend shut
$\frac{3}{4}$″ (19·1 mm.) and less thick open flat
} cold without fracture.

To be made only when required by inspector.

Rivet Steel—Bend Tests.

Diameter of loop, Flat.
Break, Gradual.

Appearance, Fine, silky, uniform fracture.

If the ultimate strength varies more than 4,000 lbs./sq. in. (2·8 kg./mm.²) from that desired, a re-test to be made which, to be acceptable, shall be within 5,000 lbs. (3·5 kg./mm.²) of desired ultimate.

Check analysis shall be made from finished material, if called for by purchaser; excess of 25 per cent. allowed.

Structural Steel for Buildings.

	Tensile Strength, lbs./sq. in.	Elongation. l	Elongation. 1,400,000 / Tensile Strength, per cent.
Structural Steel	55,000 to 65,000 (38·7-45·7 kg./mm.²)	8 ins. (203·2)	≧ 23
Rivet Steel	48,000 to 58,000 (33·7-40·8 kg./mm.²)	8 ins. (203·2)	≧ 24

Medium steel $\frac{3}{4}$″ (19·1 mm.) and less thick, test specimen shall be of same thickness as of material from which it is cut, but for material thicker than $\frac{3}{4}$″ (19·1 mm.), test piece may be ½″ (12·7 mm.) thick. Width for both 1½″ (38·1 mm.)

Test.—Medium steel shall bend cold 180° around a diameter equal to thickness of specimen tested, without fracture on outside bend.

Bend cold, 180° flat, without fracture on outside of bent portion.

Should test piece break outside of the middle third of gauged length, another test piece substituted therefor.

With regard to permissible variations from specified weight and dimensions, there exist special regulations for plates. For all other steel parts, the variation in cross-section and weight of the single pieces may amount to 2½ per cent. at the most.

SPECIFICATIONS FOR STEEL RAILS.

		Germany.		Great Britain.			U.S.A.	
		Rails and Tongue Rails.	Tramway Rails.	Flat Bottom Railway Rails.	Bull Head Railway Rails.	Tramway Rails.	Rails.	O.H. Rails.
1	Material	Ingot Steel.		Steel.			Bessemer Steel.	Open Hearth Steel.
2	Process of Manufacture	Optional, to be specified, however, in tender.		Optional, the purchaser, however, to approve.			Specified in Contract.	
3	Finish	No cracks, fuse holes, injurious seams, burrs or defects of every kind. Square at ends.	—	Uniform section throughout, true to templates, perfectly sound and straight and free from splits, cracks, burrs and defects of any kind.		Uniform section throughout, accurately rolled to conform to template, perfectly sound and free from twists, blisters, flaws, fins and other defects.	Straight in line and surface, smooth on head, sawed square at ends, no burrs, and the ends made clean. Not to vary throughout their entire length 5 inches (127 mm.) from a straight line in any direction, when delivered to the cold straightening presses.	
4	Chemical Analysis	Not required.		Carbon and Phosphorus determinations of each cast. An analysis representing average of other elements in steel, to be given for each rolling up to 200 tons each. When rolling exceeds 200 tons an additional complete analysis to be made for each 200 tons or part thereof.	Carbon determinations of each cast. An analysis representing average of other elements in steel, to be given for each rolling up to 200 tons each. When rolling exceeds 200 tons an additional complete analysis to be made for each 200 tons or part thereof.	Carbon determinations of each cast. An analysis representing average of other elements in steel, to be given for each rolling up to 100 tons each. When rolling exceeds 100 tons an additional complete analysis to be made for each 100 tons or part thereof.	Daily carbon determinations for each blow, and a complete analysis every 24 hours, representing average of other elements in steel, for each day and night turn.	Determinations for each heat of all the elements specified.
5	Chemical Composition—per cent.							
	Carbon	—	—	0·35-0·5	0·35-0·5	0·4-0·55	0·35–0·55, 0·45–0·55	0·46–0·59, 0·62–0 75
	Phosphorus	—	—	0·07 not to exceed	0·075 not to exceed	0·08 not to exceed.	0·1 not to exceed	0·04 not to exceed
	Silicon	—	—	0·1 " " "	0·1 " " "	0·1 " " "	0·2 " " "	0·20 " " "
	Manganese	—	—	0·7-1·0	0·7-1·0	0·7-1·0	0·7–1·00, 0·84–1·14	0·60-0·90
	Sulphur	—	—	0·07 not to exceed	0·08 not to exceed	0·08 not to exceed	—	—

6	Section	According to template furnished by purchaser.	Each section to be accurately rolled to its respective template. 2 sets of templates (internal and external) supplied by manufacturer upon request of purchaser.			According to template furnished by purchaser.	
7	Branding	Each rail to have manufacturers' mark and year, either when manufactured or when put into use, in raised letters, also number of blow. All on web.	Brand (see sketch) rolled on web, "B.S.," number process of manufacture, name, initials or other recognised mark and month and year of manufacture rolled in ¾ inch (19·0 mm.) letters, and the number of the cast or blow stamped in ½ inch (12·7 mm.) block figures on end of each rail.		Same, without mention being made of month.	Name of maker, weight of rail, and month and year of manufacture rolled in raised letters on the web, and number of blow stamped on each rail.	Name of maker, weight of rail, and month and year of manufacture rolled in raised letters on the web, and number of melt and the letters O. H. stamped on each rail.
8	Impact Test— Drop	The rails have to stand the following tests: For rails weighing from 47½ lbs /yd. (23·8 m./kg.) and over, 10,850 ft./lbs. (1,500 m./kg.) For rails weighing from 40½ lbs./yd. (20 m./kg.) and down to 47½ lbs./yd. (23·8 m./kg.), 7,233 ft./lbs. (1,000 m./kg.) For rails weighing from 32½ lbs /yd. (16 m./kg.) down to 40½ lbs./yd. (20 m./kg), 5,424 ft./lbs. (750 m./kg.)	The first blow 10,850 ft./lbs. (1,500 m./kg.); the others 8,680 ft./lbs. (1,200 m./kg.)	8-30 ft. (2·44-9·14m.) In 17 stages for rails of 20-100 lbs./yard (9·9-49·5 kg/m.	5-7 ft (1·52-2·12m.) 1st blow. 10-20 ft. (3·05-6·10m.) 2nd blow. In 9 stages for rails of 60-100 lbs./yard (30-50 kg./m.)	15 ft. (4·57 m.) for rails less than 100 lbs./yd. (49·5 kg./m.) 18 ft. (5·48 m.) for rails of and exceeding 100 lbs./yd. (49·5 kg./m.)	15-18 ft. (4·57-5·48 m.) In 5 stages for rails of 50-100 lbs /yard. (24·8-99·5 kg./m.)
	Weight of Tup	560-2240 lbs. (254-1016kg.)		2,240 lbs. (1,016 kg.)		At least 2,240 lbs. (1,016 kg.)	2,000 lbs. (906 kg.)
	Length of Test Piece	4 ft. 3 1/16 in. (1·3 m.)	5 ft. (1·52 m.)	5 ft. (1·52 m.)		5 ft. (1·52 m.)	Anvil block of 20,000 lbs. (9,060 kg.) at least in standardised drop testing machine in general use to be described.
	Centres of Bearings	3 ft. 3 ins. (1 m.)	For 20-65 lbs./yd. (9·9-32 kg./m.) 3 ft. (0·9 m.) For 70-100 lbs./yd. (34·7-49·5 kg./m.) 3½ ft. (1·07 m.)	3 ft. 6 ins. (1·07 m.)		3 ft. 6 ins. (1·07 m.)	4-6 ft. (1·22-1·83 m.) 3 ft. (0·91 m.)

SPECIFICATIONS FOR STEEL RAILS.—*Continued.*

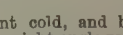
		Germany.		Great Britain.			U.S.A.	
		Rails and Tongue Rails.	Tramway Rails.	Flat Bottom Railway Rails.	Bull Head Railway Rails.	Tramway Rails.	Rails.	O.H. Rails.
8	Impact Test—*Continued.* Number of Blows -	Until required deflection.		1 blow.	2 blows.	1 blow.	1 blow.	
	Required Deflection	At least 3 1/16 in. (100 mm.) for section of height 5 5/16 in. (134 mm.) and at least 5 1/4 in. (130 mm.) for tongue rails. For other sections including tongue rails, *vice versâ* proportionately to the heights of sections.	At least 2 3/8 in. (60 mm.) with sections up to height of 5 1/16 in. (150 mm.): beyond that at least 1 3/16 in. (50 mm.)	—	From 1-1 5/16″ (25·4-33·3 mm.) to 1 5/16-1 5/8″ (22·2-33·3 mm.) 1st blow, according to weight of section. From 3-3 3/4″ (76·2-95·2 mm.) to 3-4 1/4″ (76·2-108·0 mm.) 2nd blow, ditto.	—	—	—
	Number of Tests -	1 test for each lot of 200 rails and portion thereof.		1 test from each cast, in addition one finished rail from every 200 offered.	1 test from each cast.	1 test from each 80 rails.	1 test from every cast.	
9	Tensile Tests—			Diameter (14·3 mm.) 0·564 in.	Diameter (20·3 mm.) 0·798 in.			
	Dimensions of Test Piece	3 1/2 inch (25 mm.) diameter, 7 1/8 inches (200 mm.) length from centre of rail-head of pieces which have been subjected to impact test.		Area (161·3 mm².) 1/4 sq. in. Gauge length (50·8 mm.) 2″. Parallel for a length of not less than (57·2 mm.) 2 1/4 ins.	(322·6 mm².) 1/2 sq. in. (76·2 mm.) 3 ins. (85·7 mm.) 3 3/8 ins.	(50·8 mm.) 2 in. long. (322·6 mm.²) 1/2 sq. in. approximate sectional area.	Not called for.	
	Tensile Strength -	min. 39 t. p. sq. in. (60 kg./mm.²)	min. 46 t. p. sq. in. (70 kg./mm.²)	(63-75·6 kg./mm.²) 40-48 t. p. sq. in.	(59·9-70·9 kg./mm.²) 40-48 t. p. sq. in.	(63 kg./mm.²) at least 40 t./sq. in.		
	Elongation - -	To be given.		15 per cent. (min.)	15 per cent. (min.)	10 1/2 per cent.		
	Number of Tests -	1 test for each lot of 200 rails and portion thereof.		1 test for each 100 tons rails.	1 test for each 100 tons rails.	1 test for each 100 tons rails.		

10	Rejection - -	Should the test piece fail to comply with the impact and ten-ile tests, a second and eventually a third rail is taken from the same cast. Should one of these fail to fulfil the specified requirements all the rails belonging to such cast may be rejected. The whole delivery can be rejected if on testing no settled conviction is arrived at of the faultless condition of the rails, or, if after the rails are accepted, defects or defaults, arise showing that the rails have not been made in accordance with the specified condition.		Should the length cut from the selected rail fail to comply with the drop test specified, two other rails from same cast will be selected, both of which must comply with specified requirements or cast will be rejected. Should the test piece fail to comply with the tensile test, two other rails may be taken from the same cast, both of which must comply with the specified requirement or cast will be rejected. The engineer may then take similar test pieces from two other rails out of the same 100 tons and should either fail whole 100 tons may be rejected.	If the test piece fractures under drop test, all rails from that cast may be rejected, unless it is shown from similar trial on two further pieces of rail that first piece was not fairly representative of quality of steel. Should test piece fail to comply with tensile test another rail may be taken from the same cast, and it must fulfil specified requirements or cast will be rejected.	If any rail breaks under drop test, two additional tests will be made from same cast, and if either of latter tests fail all rails of such blow will be rejected.
11	Permissible Variations. (*a*) Dimensions— In Length - -	Up to 29½ ft. (9 m.) ± 1/12 in. (2 mm.) Above 29½ ft. (9 m.) ± ⅛ in. (3 mm.) No variation in the case of tongue rails.	Up to 39 ft. 4 in. (12 m.) ± ⅛ in. (3 mm.)	Normal length, 9·144, 10·973, 13·716 or 18·288 m. (30, 36, 45 or 60 ft.) ± 3/16 in. (4·8 mm.) specified length.	Normal length, 10·668, 13·716 or 18·288 m. (35, 45 or 60 ft.) 2½-5 per cent. shorter as specified. ± ¼ in. (6·3 mm.) from the lengths specified.	Normal length, 30 and 33 feet (9·144 and 10·058 m.) 10 per cent. of order will be accepted in length varying by even feet to 24 feet (7·312 m.) ± ¼ in. (6·35 mm.) specified length.
		5 per cent. of contract may be shorter than specified.		7½ per cent. of contract may be shorter than specified.		
	In Straightness -	Warped rails not accepted.	Up to ⅛ in. (3 mm.) for 29½ ft. (9 m.) vertically and horizontally. Those warped rails which are more than ± 1/17 in (± 1·5 mm.) from the straight will not be accepted.			Square at ends not over 1/32 in. (0·8 mm.) variation. Must be straight in line and surface.

SPECIFICATIONS FOR STEEL RAILS.—*Continued.*

		Germany.		Great Britain.			U.S.A.	
		Rails and Tongue Rails.	Tramway Rails.	Flat Bottom Railway Rails.	Bull Head Railway Rails.	Tramway Rails.	Rails.	O.H. Rails.
11	Permissible Variations—*Continued* In position and size of holes -	± $\frac{1}{25}$ in. (1 mm.)	± $\frac{1}{25}$ in. (1 mm.)	± $\frac{1}{32}$ in. (0·8 mm.)	± $\frac{1}{32}$ in. (0·8 mm.)	For fish bolts $\frac{1}{16}$ in. (1·6 mm.)	Must accurately conform to drawing.	
	In width of head -	± $\frac{1}{50}$ in. (0·5 mm.)	± $\frac{1}{25}$ in. (1 mm.)				$\frac{1}{16}$ in. (1·6 mm.)	
	In thickness of web	± $\frac{1}{50}$ in (0·5 mm.)	± $\frac{1}{25}$ in. (1 mm.)					
	In width of bottom	± $\frac{1}{25}$ in. (1 mm.)	± $\frac{1}{12}$ in. (2 mm.)				$\frac{1}{16}$ in. (1·6 mm.)	
	In height - -	± $\frac{1}{50}$ in. (0 5 mm.)	± $\frac{1}{25}$ in. (1 mm.)			± $\frac{1}{32}$ in. (0·8 mm.) Distance between fishing angles ± $\frac{1}{64}$ in. (0·4 mm.)	− $\frac{1}{64}$ in. to + $\frac{1}{32}$ in. (0·4 to + 0·8 mm.)	
	(*b*) Weight -	+ 3 per cent. to − 2 per cent. Additional weight up to 1 per cent. will be paid for, otherwise the actual weight. Normal weight being the actual weight of 50 faultlessly rolled rails.	+ 4 per cent. to − 3 per cent. Additional weight up to 1 per cent. will be paid for, otherwise the actual weight. Normal weight being the actual weight of 50 faultlessly rolled rails.	± ½ per cent. calculated weight, but actual weight only paid for.		Max. 1 lb. per yard (0·5 kg./m.)	± ½ per cent. accepted and paid for according to actual weight. The finishing temperature in rolling is controlled by the amount of shrinkage, not more than $6\frac{7}{16}$ inches (163·5 mm.) allowed per 33 feet (10·058 m.) 75-lb. rail (37·2 kg./m.), with $\frac{1}{16}$ (1·6 mm.) increase per each increase of 5 lbs. (2·5 kg) in the weight of the section.	

SPECIFICATIONS FOR FISH PLATES.

		Germany.	Great Britain.	U.S.A.
		Fish Plates for Railway and Tramway Rails.	Fish Plates for Tramway Rails.	Splice Bars.
1	Material	Ingot Steel.	Steel.	—
2	Process of Manufacture	Optional, to be specified, however, in tenders.	Optional, but the steel shall be in all respects similar to that used in the manufacture of the rails and to be approved by purchaser.	Bessemer or Open Hearth.
3	Finish	According to template, smoothly and cleanly rolled. No cracks, fuse holes, defective edges or other defects. Perfectly straight.	Conforming to template, quite straight and smooth on all bearing surfaces, free from twists, cracks, blisters or other defects and shall have all fins and burrs carefully removed.	Smoothly rolled and true to template. Sheared accurately to length and free from fins or cracks and shall perfectly fit the rails. Punching and notching shall accurately conform in every respect to drawings and dimensions furnished. Phosphorus not over 0·10.
4	Chemical Analysis	—	According to the requirements specified for Rails.	
5	Branding	Manufacturer's mark, year of delivery, shown by last 2 figures, number mentioned on drawing.	Brand, "B.S.," Number, Manufacturers' Name (initials) and year of manufacture, rolled in raised letters of at least ½ in. (12·7 mm.) in size.	The name of the maker and year of manufacture shall be rolled in raised letters on the side of the splice bar.
6	Physical Tests— Tensile Tests	Ingot Steel of 24½ to 32 t./sq. in. (38-50 kg./mm.²) Ingot Steel of 32 to 39 t./sq. in. (50-60 kg./mm.²)	At least 40 t./sq. in. (63·0 kg/mm.²). In accordance with the requirements specified for Tramway Rails.	54,000-64,000 lbs. per sq. in. (37·9-45·0 kg./mm.²). Elongation in 8 ins. (203·2 mm.) not less than 25 per cent.
	Bending Test— Span / Permanent Deflection	(16½ in.) 420 mm. min. (½ in.) 6 mm.	Capable of being bent cold, and before being punched, to a right angle round a bar 4 ins. (101·6 mm.) in diameter, without showing fracture on outside.	180° flat 
	Wedging Test— (Aufkeilprobe)	At the front opening of the clinch (Klinke) at least $\frac{1}{12}$ in (2 mm.) with a wedge inclined at 1 : 20.	—	A full sized bar first flattened and then bent 180° flat.
	Number of Tests	1 test for each 500 Fish Plates.	(Same as for Tramway Rails) 1 test for each 100 ton.	—
7	Rejection of Fish Plates	If 2 from each 100 of a part delivery submitted for acceptance fail to comply with specified requirements the whole of such part delivery may be rejected.	(Same as for Tramway Rails.) If the test piece fails to comply with the specifications, another test piece of same cast will be tested.	1 test from each blow or melt. Each blow or melt accepted or rejected on results of tests from that blow or melt.
8	Permissible Variations. (*a*) Dimensions— In length	± ⅛ in. (3 mm.)	—	Must be rolled true to template.
	In position and size of holes	± $\frac{1}{50}$ in. (0·5 mm.)	± $\frac{1}{16}$ in. (1·6 mm.)	
	In bearing face	+ $\frac{1}{100}$ in. (0·25 mm.)	—	
	In thickness	± $\frac{1}{50}$ in. (0·5 mm.)	—	
	In other dimensions	± $\frac{1}{25}$ in. (1 mm.)	—	
	In distance of clinches (Im Abstande der Einkinkungen)	± $\frac{1}{12}$ in. (2 mm.)	—	
	In size of clinches	± $\frac{1}{25}$ in. (1 mm.)	—	
	(*b*) Weight	+ 3 per cent. to − 2 per cent. Additional weight is paid for up to 1 per cent.	Actual weight is paid for.	Actual weight is paid for.

APPENDIX II.

Table showing Relation of Percentage of Carbon to Tensile Stress.

It is extremely difficult to give the tensile stress corresponding to different percentages of Carbon in commercial steels, as the strength of the material for the same Carbon content will vary according to the process of manufacture, the size of the finished section, and the percentages of other impurities present. The following table gives, approximately, what may be expected from steel of good quality in which the Manganese does not exceed ·8 per cent. When Manganese is above ·8, the tensile stress will be considerably higher. The table has been compiled from a large number of published results, and from the author's private records. The tensile stress for basic steels above ·5 is not given, as so little high Carbon basic steel is made in this country that a sufficient number of samples have not been available to obtain a fair average.

Acid Bessemer and basic Bessemer steels will not differ greatly from open hearth steel in tensile strength, especially in the low Carbon steels, and comparatively little high Carbon steel is made by these processes, except for rails.

Acid Open Hearth Steel.			Basic Open Hearth Steel.		
Carbon per cent.	Tensile Stress.		Carbon per cent.	Tensile Stress.	
	Tons per Square Inch.	Lbs. per Square Inch.		Tons per Square Inch.	Lbs. per Square Inch.
·05 to ·10	21 to 27	47,040 to 60,480	·05 to ·10	20 to 25	44,800 to 56,000
·10 ,, ·15	24 ,, 29	53,760 ,, 64,960	·10 ,, ·15	23 ,, 27	51,520 ,, 60,480
·15 ,, ·20	27 ,, 32	60,480 ,, 71,680	·15 ,, ·20	25 ,, 29	56,000 ,, 64,960
·20 ,, ·25	29 ,, 34	64,960 ,, 76,160	·20 ,, ·25	26 ,, 30	58,240 ,, 67,200
·25 ,, ·30	30 ,, 35	67,200 ,, 78,400	·25 ,, ·30	28 ,, 32	62,720 ,, 71,680
·30 ,, ·35	31 ,, 37	69,440 ,, 82,880	·30 ,, ·35	29 ,, 33	64,960 ,, 73,920
·35 ,, ·40	35 ,, 41	78,400 ,, 91,840	·35 ,, ·40	31 ,, 35	69,440 ,, 78,400
·40 ,, ·45	39 ,, 45	87,360 ,, 100,800	·40 ,, ·45	34 ,, 40	76,160 ,, 89,600
·45 ,, ·50	43 ,, 48	96,320 ,, 107,520	·45 ,, ·50	38 ,, 43	85,120 ,, 96,320
·50 ,, ·55	47 ,, 53	105,280 ,, 118,920			
·55 ,, ·60	50 ,, 55	112,000 ,, 123,200			
·60 ,, ·65	52 ,, 57	116,480 ,, 127,680			
·65 ,, ·70	55 ,, 60	123,200 ,, 134,400			
·70 ,, ·75	58 ,, 62	129,920 ,, 138,880			
·75 ,, ·80	60 ,, 64	134,400 ,, 143,360			
·80 ,, ·85	61 ,, 65	136,640 ,, 145,600			
·85 ,, ·90	63 ,, 67	141,120 ,, 150,800			

Note to Table C. (pp. 517-521).

To obtain the relation of stresses over 50 tons on the square inch, multiply or add two of the lines of figures given in the table. For instance, to find the number of kilos. per square mm. answering to 60 or 65 tons on the square inch:—

Multiplication.

30 tons per square inch = 47·25 kilos. per square millimetre.
2 2
60 ,, ,, = 94·50 ,, ,,

Addition.

50 tons per square inch = 78·75 kilos. per square millimetre.
15 ,, ,, = 23·62 ,, ,,
65 ,, ,, = 102·37 ,, ,,

APPENDIX III.

TABLE C.—Showing how Tons per Square Inch and Lbs. per Square Inch compare with Kilogrammes per Square Millimetre.

(Calculated by John W. Hall.)

Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.	Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.	Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.
10·00	22,400	15·75	12·55	28,112	19·77	15·05	33,712	23·70
10·05	22,512	15·83	12·60	28,224	19·84	15·10	33,824	23·78
10·10	22,624	15·91	12·65	28,336	19·92	15·15	33,936	23·86
10·15	22,736	15·99	12·70	28,448	20·00	15·20	34,048	23·94
10·20	22,848	16·06	12·75	28,560	20·08	15·25	34,160	24·02
10·25	22,960	16·14	12·80	28,672	20·16	15·30	34,272	24·10
10·30	23,072	16·22	12·85	28,784	20·24	15·35	34,384	24·18
10·35	23,184	16·30	12·90	28,896	20·32	15·40	34,496	24·25
10·40	23,296	16·38	12·95	29,008	20·40	15·45	34,608	24·33
10·45	23,408	16·46				15·50	34,720	24·41
10·50	23,520	16·54	13·00	29,120	20·47	15·55	34,832	24·49
10·55	23,632	16·62	13·05	29,232	20·55	15·60	34,944	24·57
10·60	23,744	16·69	13·10	29,344	20·63	15·65	35,056	24·65
10 65	23,856	16·77	13·15	29,456	20·71	15·70	35,168	24·73
10·70	23,968	16·85	13·20	29,568	20·79	15·75	35,280	24·81
10·75	24,080	16·93	13·25	29,680	20·87	15·80	35,392	24·88
10·80	24,192	17·01	13·30	29,792	20·95	15·85	35,504	24·96
10·85	24,304	17·09	13·35	29,904	21·03	15·90	35,616	25·04
10·90	24,416	17·17	13·40	30,016	21·10	15·95	35,728	25·12
10·95	24,528	17·25	13·45	30,128	21·18			
			13·50	30,240	21·26	16·00	35,840	25·20
11·00	24,640	17·32	13·55	30,352	21·34	16·05	35,952	25·28
11·05	24,752	17·40	13·60	30,464	21·42	16·10	36,064	25·36
11·10	24,864	17·48	13·65	30,576	21·50	16·15	36,176	25·44
11·15	24,976	17·56	13·70	30,688	21·58	16·20	36,288	25·51
11·20	25,088	17·64	13·75	30,800	21·66	16·25	36,400	25·59
11·25	25,200	17·72	13·80	30,912	21·73	16·30	36,512	25·67
11·30	25,312	17·80	13·85	31,024	21·81	16·35	36,624	25·75
11·35	25,424	17·88	13·90	31,136	21·89	16·40	36,736	25·83
11·40	25,536	17·95	13·95	31,248	21·97	16·45	36,848	25·91
11·45	25,648	18·03				16·50	36,960	25·99
11·50	25,760	18·11	14·00	31,360	22·05	16·55	37,072	26·07
11·55	25,872	18·19	14·05	31,472	22·13	16·60	37,184	26·14
11·60	25,984	18·27	14·10	31,584	22·21	16·65	37,296	26·22
11·65	26,096	18·35	14·15	31,696	22·29	16·70	37,408	26·30
11·70	26,208	18·43	14·20	31,808	22·36	16·75	37,520	26·38
11·75	26,320	18·51	14·25	31,920	22·44	16·80	37,632	26·46
11·80	26,432	18·58	14·30	32,032	22·52	16·85	37,744	26·54
11·85	26,544	18·66	14·35	32,144	22·60	16·90	37,856	26·62
11·90	26,656	18·74	14·40	32,256	22·68	16·95	37,968	26·70
11·95	26,768	18·82	14·45	32,368	22·76			
			14·50	32,480	22·84	17·00	38,080	26·77
12·00	26,880	18·90	14·55	32,592	22·92	17·05	38,192	26·85
12·05	26,992	18·98	14·60	32,704	22·99	17·10	38,304	26·93
12·10	27,104	19·06	14·65	32,816	23·07	17·15	38,416	27·01
12·15	27,216	19·14	14·70	32,928	23·15	17·20	38,528	27·09
12·20	27,328	19·21	14·75	33,040	23·23	17·25	38,640	27·17
12·25	27,440	19·29	14·80	33,152	23·31	17·30	38,752	27·25
12·30	27,552	19·37	14·85	33,264	23·39	17·35	38,864	27·33
12·35	27,664	19·45	14·90	33,376	23·47	17·40	38,976	27·40
12·40	27,776	19·53	14·95	33,488	23·55	17·45	39,088	27·48
12·45	27,888	19·61				17·50	39.200	27·56
12·50	28,000	19·69	15·00	33,600	23·62	17·55	39,312	27·64

TABLE C.—*Continued.*

Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.	Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.	Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.
17·60	39,424	27·72	20·30	45,472	31·97	23·00	51,520	36·22
17·65	39,536	27·80	20·35	45,584	32·05	23·05	51,632	36·30
17·70	39,648	27·88	20·40	45,696	32·13	23·10	51,744	36·38
17·75	39,760	27·96	20·45	45,808	32·21	23·15	51,856	36·46
17·80	39,872	28·03	20·50	45,920	32·29	23·20	51,968	36·54
17·85	39,984	28·11	20·55	46,032	32·37	23·25	52,080	36·62
17·90	40,096	28·19	20·60	46,144	32·44	23·30	52,192	36·70
17·95	40,208	28·27	20·65	46,256	32·52	23·35	52,304	36·78
			20·70	46,368	32·60	23·40	52,416	36·85
18·00	40,320	28·35	20·75	46,480	32·68	23·45	52,528	36·93
18·05	40,432	28·43	20·80	46,592	32·76	23·50	52,640	37·01
18·10	40,544	28·51	20·85	46,704	32·84	23·55	52,752	37·09
18·15	40,656	28·59	20·90	46,816	32·92	23·60	52,864	37·17
18·20	40,768	28·66	20·95	46,928	32·99	23·65	52,976	37·25
18·25	40,880	28·74				23·70	53,088	37·33
18·30	40,992	28·82	21·00	47,040	33·07	23·75	53,200	37·41
18·35	41,104	28·90	21·05	47,152	33·15	23·80	53,312	37·48
18·40	41,216	28·98	21·10	47,264	33·23	23·85	53,424	37·56
18·45	41,328	29·06	21·15	47,376	33·31	23·90	53,536	37·64
18·50	41,440	29·14	21·20	47,488	33·39	23·95	53,648	37·72
18·55	41,552	29·22	21·25	47,600	33·47			
18·60	41,664	29·29	21·30	47,712	33·55	24·00	53,760	37·80
18·65	41,776	29·37	21·35	47,824	33·63	24·05	53,872	37·88
18·70	41,888	29·45	21·40	47,936	33·70	24·10	53,984	37·96
18·75	42,000	29·53	21·45	48,048	33·78	24·15	54,096	38·04
18·80	42,112	29 61	21·50	48,160	33·86	24·20	54,208	38·11
18·85	42,224	29·69	21·55	48,272	33·94	24·25	54,320	38·19
18·90	42,336	29·77	21·60	48,384	34·02	24·30	54,432	38·27
18·95	42,448	29·85	21·65	48,496	34·10	24·35	54,544	38·35
			21·70	48,608	34·18	24·40	54,656	38·43
19·00	42,560	29·92	21·75	48,720	34·26	24·45	54,768	38·51
19·05	42,672	30·00	21·80	48,832	34 33	24·50	54,880	38·59
19·10	42,784	30·08	21·85	48,944	34·41	24·55	54,992	38·67
19·15	42,896	30·16	21·90	49,056	34·49	24·60	55,104	38·74
19·20	43,008	30·24	21·95	49,168	34·57	24·65	55,216	38·82
19·25	43,120	30·32				24·70	55,328	38·90
19·30	43,232	30·40				24·75	55,440	38·98
19·35	43,344	30·48	22·00	49,280	34·65	24·80	55,552	39·06
19·40	43,456	30·55	22·05	49,392	34·73	24·85	55,664	39·14
19·45	43,568	30·63	22·10	49,504	34·81	24·90	55,776	39·22
19·50	43,680	30·71	22·15	49,616	34·89	24·95	55,888	39·30
19·55	43,792	30·79	22·20	49,728	34·96			
19·60	43,904	30·87	22·25	49,840	35·04	25·00	56,000	39·37
19·65	44,016	30·95	22·30	49,952	35·12	25·05	56,112	39·45
19·70	44,128	31·03	22·35	50,064	35·20	25·10	56,224	39·53
19·75	44,240	31·11	22·40	50,176	35·28	25·15	56,336	39·61
19·80	44,352	31·18	22·45	50,288	35·36	25·20	56,448	39·69
19·85	44,464	31·26	22·50	50,400	35·44	25·25	56,560	39·77
19·90	44,576	31·34	22·55	50,512	35·52	25·30	56,672	39·85
19·95	44,688	31·42	22·60	50,624	35·59	25·35	56,784	39·93
			22·65	50,736	35·67	25·40	56.896	40·00
20·00	44,800	31·50	22·70	50.848	35·75	25·45	57,008	40·08
20·05	44,912	31·58	22·75	50,960	35·83	25·50	57,120	40·16
20·10	45,024	31·66	22·80	51,072	35·91	25·55	57,232	40·24
20·15	45,136	31·74	22·85	51,184	35·99	25·60	57,344	40·32
20·20	45,248	31·81	22·90	51,296	36·07	25·65	57,456	40·40
20·25	45,360	31·89	22·95	51,408	36·15	25·70	57,568	40·48

TABLE C.—*Continued.*

Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.	Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.	Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.
25·75	57,680	40·56	28·45	63,728	44·81	31·15	69,776	49·06
25·80	57,792	40·63	28·50	63,840	44·89	31·20	69,888	49·14
25·85	57,904	40·71	28·55	63,952	44·97	31·25	70,000	49·22
25·90	58,016	40·79	28·60	64,064	45·04	31·30	70,112	49·30
25·95	58,128	40·87	28·65	64,176	45·12	31·35	70,224	49·38
			28·70	64,288	45·20	31·40	70,336	49·45
26·00	58,240	40·95	28·75	64,400	45·28	31·45	70,448	49·53
26·05	58,352	41·03	28·80	64,512	45 36	31·50	70,560	49·61
26·10	58,464	41·11	28 85	64,624	45 44	31·55	70,672	49·69
26·15	58,576	41·19	28·90	64,736	45·52	31·60	70,784	49·77
26·20	58,688	41·26	28·95	64,848	45·60	31·65	70,896	49·85
26·25	58,800	41·34				31·70	71,008	49·93
26·30	58,912	41·42	29·00	64,960	45·67	31·75	71,120	50·01
26·35	59,024	41·50	29·05	65,072	45·75	31·80	71,232	50·08
26·40	59,136	41·58	29·10	65,184	45 83	31·85	71,344	50·16
26·45	59,248	41·66	29·15	65,296	45·91	31·90	71,456	50·24
26·50	59,360	41·74	29·20	65,408	45·99	31·95	71,568	50·32
26·55	59,472	41·82	29·25	65,520	46·07			
26·60	59.584	41·89	29·30	65,632	46·15	32·00	71,680	50·40
26·65	59,696	41·97	29·35	65,744	46·23	32·05	71,792	50·48
26·70	59,808	42·05	29·40	65,856	46·30	32·10	71,904	50·56
26·75	59,920	42·13	29·45	65,968	46·38	32·15	72,016	50·64
26 80	60,032	42·21	29·50	66,080	46·46	32·20	72,128	50·71
26·85	60,144	42·29	29·55	66,192	46·54	32·25	72,240	50·79
26·90	60,256	42·37	29·60	66,304	46·62	32·30	72,352	50·87
26·95	60,368	42·45	29·65	66,416	46·70	32·35	72,464	50·95
			29·70	66,528	46·78	32·40	72,576	51·03
27·00	60,480	42·52	29·75	66,640	46·86	32·45	72,688	51·11
27·05	60,592	42·60	29·80	66,752	46·93	32·50	72,800	51·19
27·10	60,704	42·68	29·85	66,864	47·01	32·55	72,912	51·27
27·15	60,816	42·76	29·90	66,976	47·09	32·60	73,024	51·34
27·20	60,928	42·84	29·95	67,088	47·17	32·65	73,136	51·42
27·25	61,040	42·92				32·70	73,248	51·50
27·30	61,152	43·00	30·00	67,200	47·25	32·75	73,360	51·58
27·35	61,264	43·08	30·05	67,312	47·33	32·80	73,472	51 66
27·40	61,376	43·15	30·10	67,424	47·41	32·85	73,584	51·74
27·45	61,488	43·23	30·15	67,536	47·49	32·90	73,696	51·82
27·50	61,600	43·31	30·20	67,648	47 56	32·95	73,808	51·90
27·55	61,712	43·39	30·25	67,760	47·64			
27·60	61,824	43·47	30·30	67,872	47·72	33·00	73,920	51·97
27·65	61,936	43·55	30·35	67,984	47·80	33·05	74,032	52·05
27·70	62,048	43·63	30·40	68,096	47·88	33·10	74,144	52·13
27·75	62,160	43·71	30·45	68,208	47·96	33·15	74,256	52·21
27·80	62,272	43·78	30·50	68,320	48·04	33·20	74,368	52·29
27·85	62,384	43·86	30·55	68,432	48·12	33·25	74,480	52·37
27·90	62,496	43·94	30·60	68,544	48·19	33·30	74,592	52·45
27·95	62,608	44·02	30·65	68,656	48·27	33·35	74,704	52·53
			30·70	68,768	48 35	33·40	74,816	52·60
28·00	62,720	44·10	30·75	68,880	48·43	33·45	74,928	52·68
28·05	62,832	44·18	30·80	68,992	48·51	33·50	75,040	52·76
28·10	62,944	44·26	30·85	69,104	48·59	33·55	75,152	52·84
28·15	63,056	44·34	30·90	69,216	48·67	33·60	75,264	52·92
28·20	63,168	44·41	30·95	69,328	48·75	33·65	75,376	53·00
28·25	63,280	44·49				33·70	75,488	53·08
28·30	63.392	44·57	31·00	69,440	48·82	33·75	75,600	53·16
28·35	63,504	44·65	31·05	69,552	48·90	33·80	75,712	53·23
28·40	63,616	44·73	31·10	69,664	48·98	33·85	75,824	53·31

TABLE C.—*Continued.*

Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.	Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.	Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.
33·90	75,936	53·39	36·60	81,984	57·64	39·30	88,032	61·90
33·95	76,048	53·47	36·65	82,096	57·72	39·35	88,144	61·98
			36·70	82,208	57·80	39·40	88,256	62·05
34·00	76,160	53·55	36·75	82,320	57·88	39·45	88,368	62·13
34·05	76,272	53·63	36·80	82,432	57·96	39·50	88,480	62·21
34·10	76,384	53·71	36·85	82,544	58·04	39·55	88,592	62·29
34·15	76,496	53·79	36·90	82,656	58·12	39·60	88,704	62·37
34·20	76,608	53·86	36·95	82,768	58·20	39·65	88,816	62·45
34·25	76,720	53·94				39·70	88,928	62·53
34·30	76,832	54·02	37·00	82,880	58·27	39·75	89,040	62·61
34·35	76,944	54·10	37·05	82,992	58·35	39·80	89,152	62·68
34·40	77,056	54·18	37·10	83,104	58·43	39·85	89,264	62·76
34·45	77,168	54·26	37·15	83,216	58·51	39·90	89,376	62·84
34·50	77,280	54·34	37·20	83,328	58·59	39·95	89,488	62·92
34·55	77,392	54·42	37·25	83,440	58·67			
34·60	77,504	54·49	37·30	83,552	58·75	40·00	89,600	63·00
34·65	77,616	54·57	37·35	83,664	58·83	40·05	89,712	63·08
34·70	77,728	54·65	37·40	83,776	58·90	40·10	89,824	63·16
34·75	77,840	54·73	37·45	83,888	58·98	40·15	89,936	63·24
34·80	77,952	54·81	37·50	84,000	59·06	40·20	90,048	63·31
34·85	78,064	54·89	37·55	84,112	59·14	40·25	90,160	63·39
34·90	78,176	54·97	37·60	84,224	59·22	40·30	90,272	63·47
34·95	78,288	55·05	37·65	84,336	59·30	40·35	90,384	63·55
			37·70	84,448	59·38	40·40	90,496	63·63
35·00	78,400	55·12	37·75	84,560	59·46	40·45	90,608	63·71
35·05	78,512	55·20	37·80	84,672	59·53	40·50	90,720	63·79
35·10	78,624	55·28	37·85	84,784	59·61	40·55	90,832	63·87
35·15	78,736	55·36	37·90	84,896	59·69	40·60	90,944	63·94
35·20	78,848	55·44	37·95	85,008	59·77	40·65	91,056	64·02
35·25	78,960	55·52				40·70	91,168	64·10
35·30	79,072	55·60	38·00	85,120	59·85	40·75	91,280	64·18
35·35	79,184	55·68	38·05	85,232	59·93	40·80	91,392	64·26
35·40	79,296	55·75	38·10	85,344	60·01	40·85	91,504	64·34
35·45	79,408	55·83	38·15	85,456	60·09	40·90	91,616	64·42
35·50	79,520	55·91	38·20	85,568	60·16	40·95	91,728	64·50
35·55	79,632	55·99	38·25	85,680	60·24			
35·60	79,744	56·07	38·30	85,792	60·32			
35·65	79,856	56·15	38·35	85,904	60·40	41·00	91,840	64·57
35·70	79,968	56·23	38·40	86,016	60·48	41·05	91,952	64·65
35·75	80,080	56·31	38·45	86,128	60·56	41·10	92,064	64·73
35·80	80,192	56·38	38·50	86,240	60·64	41·15	92,176	64·81
35·85	80,304	56·46	38·55	86,352	60·72	41·20	92,288	64·89
35·90	80,416	56·54	38·60	86,464	60·79	41·25	92,400	64·96
35·95	80,528	56·62	38·65	86,576	60·87	41·30	92,512	65·05
			38·70	86,688	60·95	41·35	92,624	65·13
36·00	80,640	56·7	38·75	86,800	61·03	41·40	92,736	65·20
36·05	80,752	56·78	38·80	86,912	61·11	41·45	92,848	65·28
36·10	80,864	56·86	38·85	87,024	61·19	41·50	92,960	65·36
36·15	80,976	56·94	38·90	87,136	61·27	41·55	93,072	65·44
36·20	81,088	57·01	38·95	87,248	61·35	41·60	93,184	65·52
36·25	81,200	57·09				41·65	93,296	65·60
36·30	81,312	57·17	39·00	87,360	61·42	41·70	93,408	65·68
36·35	81,424	57·25	39·05	87,472	61·50	41·75	93,520	65·76
36·40	81,536	57·33	39·10	87,584	61·58	41·80	93,632	65·83
36·45	81,648	57·41	39·15	87,696	61·66	41·85	93,744	65·91
36·50	81,760	57·49	39·20	87,808	61·74	41·90	93,856	65·99
36·55	81,872	57·57	39·25	87,920	61·82	41·95	93,968	66·07

TABLE C—*Continued.*

Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.	Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.	Tons per Sq. In.	Lbs. per Sq. In.	Kilos. per Sq. Mm.
42·00	94,080	66·15	44·75	100,240	70·48	47·40	106,176	74·65
42·05	94,192	66·23	44·80	100,352	70·56	47·45	106,288	74·73
42·10	94,304	66·31	44·85	100,464	70·64	47·50	106,400	74·81
42·15	94,416	66·39	44·90	100,576	70·72	47·55	106,512	74·89
42·20	94,528	66·46	44·95	100,688	70·80	47·60	106,624	74·97
42·25	94,640	66·54				47·65	106,736	75·05
42·30	94,752	66·62	45·00	100,800	70·87	47·70	106,848	75·13
42·35	94,864	66·70	45·05	100,912	70·95	47·75	106,960	75·21
42·40	94,976	66·78	45·10	101,024	71·03	47·80	107,072	75·28
42·45	95,088	66·86	45·15	101,136	71·11	47·85	107,184	75·36
42·50	95,200	66·94	45·20	101,248	71·19	47·90	107,296	75·44
42·55	95,312	67·02	45·25	101,360	71·27	47·95	107,408	75·52
42·60	95,424	67·09	45·30	101,472	71·35			
42·65	95,536	67·17	45·35	101,584	71·43	48·00	107,520	75·60
42 70	95,648	67·25	45 40	101,696	71·50	48·05	107,632	75 68
42·75	95,760	67·33	45·45	101,808	71·58	48·10	107,744	75·76
42·80	95,872	67·41	45·50	101,920	71·66	48·15	107,856	75·84
42·85	95,984	67·49	45·55	102,032	71·74	48·20	107,968	75·91
42·90	96,096	67·57	45·60	102,144	71·82	48·25	108,080	75·99
42·95	96,208	67·65	45·65	102,256	71·90	48·30	108,192	76·07
			45·70	102,368	71·98	48·35	108,304	76·15
43·00	96,320	67·72	45·75	102,480	72·06	48·40	108,416	76·23
43·05	96,432	67·80	45·80	102,592	72·13	48·45	108,528	76·31
43·10	96,544	67·88	45·85	102,704	72·21	48·50	108,640	76·39
43·15	96,656	67·96	45·90	102,816	72·29	48·55	108,752	76·47
43·20	96,768	68·04	45·95	102,928	72·37	48·60	108,864	76·54
43·25	96,880	68·12				48·65	108,976	76·62
43·30	96,992	68·20				48·70	109,088	76·70
43·35	97,104	68·28	46·00	103,040	72·45	48·75	109,200	76·78
43·40	97,216	68·35	46·05	103,152	72·53	48·80	109,312	76·86
43·45	97,328	68·43	46·10	103,264	72·61	48·85	109,424	76·94
43·50	97,440	68·51	46·15	103,376	72·69	48·90	109,536	77·02
43·55	97,552	68·59	46·20	103,488	72·76	48·95	109,648	77·10
43·60	97,664	68·67	46·25	103,600	72·84			
43·65	97,776	68·75	46·30	103,712	72·92			
43·70	97,888	68·83	46·35	103,824	73·00	49·00	109,760	77·17
43·75	98,000	68·91	46·40	103,936	73·08	49·05	109,872	77·25
43·80	98,112	68·98	46·45	104,048	73·16	49·10	109,984	77·33
43·85	98,224	69·06	46·50	104,160	73·24	49·15	110,096	77·41
43·90	98,336	69·14	46·55	104,272	73·32	49·20	110,208	77·49
43·95	98,448	69·22	46·60	104,384	73·39	49·25	110,320	77·57
			46·65	104,496	73·47	49·30	110,432	77·65
44·00	98,560	69·30	46·70	104,608	73·55	49·35	110,544	77·73
44·05	98,672	69·38	46·75	104,720	73·63	49·40	110,656	77·80
44·10	98,784	69·46	46·80	104,832	73·71	49·45	110,768	77·88
44·15	98,896	69·54	46·85	104,944	73·79	49·50	110,880	77·96
44·20	99,008	69·61	46·90	105,056	73·87	49·55	110,992	78·04
44·25	99,120	69·69	46·95	105,168	73·95	49·60	111,104	78·12
44·30	99,232	69·77				49·65	111,216	78·20
44·35	99,344	69·85	47·00	105,280	74·02	49·70	111,328	78·28
44·40	99,456	69·93	47·05	105,392	74·10	49·75	111,440	78·36
44·45	99,568	70·01	47·10	105,504	74·18	49·80	111,552	78·43
44·50	99,680	70·09	47·15	105,616	74·26	49·85	111,664	78·51
44·55	99,792	70·17	47·20	105,728	74 34	49·90	111,776	78·59
44·60	99,904	70·24	47·25	105,840	74·42	49·95	111,888	78·67
44·65	100,016	70·32	47·30	105,952	74·50			
44·70	100,128	70·40	47·35	106,064	74·58	50·00	112,000	78·75

APPENDIX IV.

RAPID DETERMINATION OF PHOSPHORUS AND MANGANESE.

THE following rapid methods of determining Phosphorus and Manganese may be found useful. The method for Phosphorus only gives comparative and very approximate results, but is useful for determining whether this constituent is above or below a certain limit in the bath of a basic Siemens furnace previous to tapping. The Manganese method gives excellent results, even as compared with the gravometric method.

PHOSPHORUS.—Solutions required—

No. 1, 400 grms. of Ammonium Nitrate + 500 c.c. Nitric Acid made up to 1,000 c.c.

No. 2, 50 grms. of Ammonium Molybdate + 100 grms. Ammonium Nitrate made up to 1,000 c.c.

·2 grm. of the steel is dissolved in 4 c.c. of No. 1 solution in a 6-inch test tube 1 inch in diameter, and is warmed; when dissolved, 4 c.c. of No. 2 solution are added, and the liquid heated to just the boiling point, diluted with hot water to a mark to fill tube one-third full, well agitated, and compared for turbidity with two standard steels, treated under identical conditions. Assuming it is necessary that the steel should contain less than ·08 per cent. Phosphorus, but not less than ·05 per cent., two standards of these percentages, respectively, are used. The comparison can be made in a few minutes, and enables the sample passer to say if the Phosphorus is well under ·08 per cent., and if the bath is ready to be tapped.

MANGANESE, WALTER'S METHOD.—Solutions—

Nitric Acid, specific gravity 1·2.

Nitrate of Silver, 1·33 grms. in 1,000 c.c. of water.

Ammonium Persulphate, 10 grms. dissolved in 30 c.c. of cold water *immediately before use.*

Dissolve ·1 grm. of steel in 5 c.c. of the acid, and heat in a water-bath until all nitrous fumes are expelled. Add 7½ c.c. of Nitrate of Silver solution and 3 c.c. of Ammonium Persulphate solution, well mix by pouring solution to and from a clean test tube, place in water-bath (not allowing water to boil), and warm for about two minutes after oxidation commences. Cool in cold water, and compare with standard steels containing known percentages of Manganese treated under identical conditions. It is absolutely necessary that fresh Ammonium Persulphate solution should be prepared every time.

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